Montpellier, January 19th, 2016

Reply to Reviewers' comments on **Determinants of modelling choices for 1-D free-surface flow and erosion issues in hydrology: a review** by Bruno Cheviron and Roger Moussa.

This document details our responses to Reviewer#1 and #2. The line numbers noted LXXX-YYY refer to the change-tracking version of the revised manuscript. The new version of the manuscript has been uploaded separately.

## Response to Reviewer #1

### *General Comment*

Overall, I liked reading this critical review of existing models that can be used for the coupled modeling of water flow and sediment transport in hydrology. I'm not a big fan of review articles in general, but in this case – provided that review articles are allowed by the journal – I express appreciation for the work and limit myself to specific comments about the manuscript. The paper is clear and well written and the review of the methods presented (at least to my knowledge) is quite complete. The English usage is correct, and the presentation of good quality. I have only a few minor comments about the manuscript:

Response (R): We thank Reviewer #1 for his positive evaluation and encouragements. We totally agree with his comments and will introduce responses in the revised version as shown below.

- I see that while the "flow" parts are discussed based on specific equations, the "sediment transport" sections are a bit more qualitative, and there are no equations there. I'm wondering if this is a deliberate choice of the authors and if they could comment a bit on this choice, maybe even in the manuscript;

R: This was indeed a deliberate choice, searching for the determinants of modelling strategies in the refinement of the flow and erosion models, then in flow typologies, then in the dimensionless numbers used.

Regarding erosion, the default/starting hypothesis was that the complexity of erosion models roughly tended to match that of the flow models to which they were associated (Section 2). However, the search for determinants of erosion modelling goes through several other stages, as announced now in Section 2.1.2. An explanation will be added L168-175.

*"On the one hand, this advocates the examination of erosion issues from the angle of decreasing refinements of the "flow and erosion" models seen as a whole (e.g. expecting the most complicated erosion processes to be out of reach of the simplest combined models). On the other hand, there might be a certain disconnection between the refinement of the flow model and that of the chosen friction and erosion models, so the determinants of modelling choices should also be sought elsewhere: in flow typologies dictated by friction and flow retardation processes but also in "erosion types", seen through a dimensionless descriptor (Section 3)."*

- Most of the paper's figures are quite dense, and I suggest to comment on these plots more broadly to guide the reader across them;

R: We agree. To do so, we will focus on a few "textbook cases", i.e. 6 cases now explicitly referred to in Fig.2, 3, 6a and 7a, shown by letters A to F, detailed in the new Table 1 and in the associated paragraph added in the corpus L507-523. The legends of the cited figures have been slightly modified to mention these textbook cases.

The new Fig.2 (L464) is hereunder and only the last sentence of its legend has been modified to mention the A to F sketches.

**Mis en forme :** Police :(Par défaut) Arial, Couleur de police : Bleu

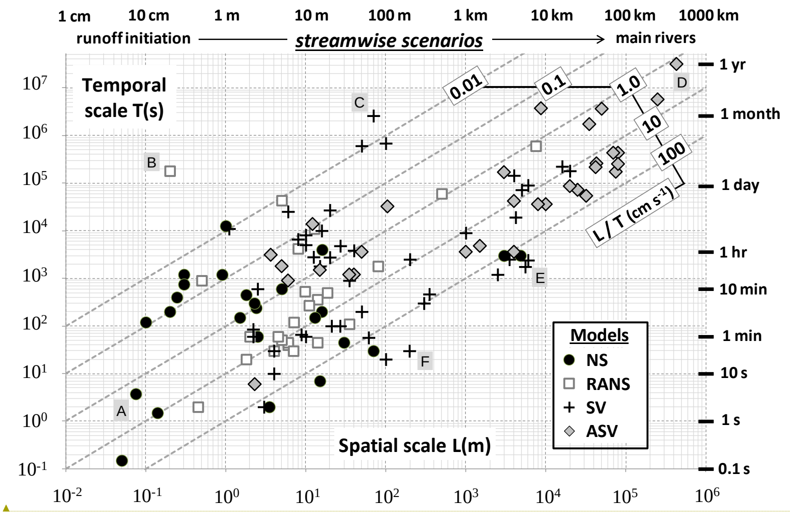


**Figure 2 – How increasing (L, T) spatiotemporal scales of the flow domain tend to be associated with decreasing complexity in the choice of flow models, sorted here into four levels of refinement: Navier-Stokes (NS), Reynolds-Averaged Navier-Stokes (RANS), Saint-Venant (SV) or Approximations to Saint-Venant (ASV). A transverse analysis involves forming L/T ratios, searching for clues to model selection according to these "system evolution velocities" or governed by flow typologies that would exhibit specific L/T ratios. This figure was assembled from information available in the studies cited in Appendix A, selecting six textbook cases (sketches A to F, Table 1) for illustration.**

The new Table 1 is the following.

| Case | Context | Authors | Model refinement | Spatiotemporal scales | | | | | Flow typology‡ | Dimensionless numbers§ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | L (m) | T (s) | H (m) | L/T (m s$^{-1}$) | H/L† (-) | | T* | Re | Fr | S (%) | $\Lambda_z$ | θ |
| A | Film flow | Charpin & Myers (2005) | NS | 0.075 | 3.75 | 0.003 | 0.02 | 0.04 | O | 5 | 300 | 0.11 | 10 | 8.0 | - |
| B | Laminar dynamics | Charru et al. (2004) | RANS | 0.2 | 1.8 $10^5$ | 0.007 | 1.1 $10^{-6}$ | 0.035 | O | 6428 | 50 | 0.02 | <0.01 | 12.1 | 0.14 |
| C | Pool-riffles | Rathburn & Wohl (2003) | SV | 70 | 2.6 $10^6$ | 0.47 | 3.5 $10^{-5}$ | 6.7 $10^{-3}$ | B | 7.8 $10^4$ | 7.1 $10^5$ | 0.69 | 1.1 | 5108 | 34.1 |
| D | Amazon River | Trigg et al. (2009) | ASV | 4.3 $10^5$ | 3.15 $10^8$ | 10 | 1.4 $10^{-3}$ | 2.3 $10^{-5}$ | F | 58.5 | 8 $10^5$ | 0.05 | <0.01 | 6600 | - |
| E | Step-pools | Grant et al. (1990) | SV | 5530 | 1755 | 0.87 | 3.15 | 1.5 $10^{-4}$ | Hg | 1.0 | 2.7 $10^6$ | 1.03 | 4.5 | 1.25 | - |
| F | Step-pools | Chin (1999) | SV | 197.25 | 30 | 0.50 | 6.58 | 0.025 | Hg | 1.21 | 4.0 $10^6$ | 3.58 | 6.25 | 1.22 | - |

† See section 3.1.2 - H/L is the fineness ratio of the flow

‡ See Section 3.2 - O: Overland, Hg: High-gradient, B: Bedforms, F: Fluvial

§ See Section 3.3 - T*: dimensionless period, Re: Reynolds number, Fr: Froude number, S: slope, $\Lambda_z$ inundation ratio, θ Shields number

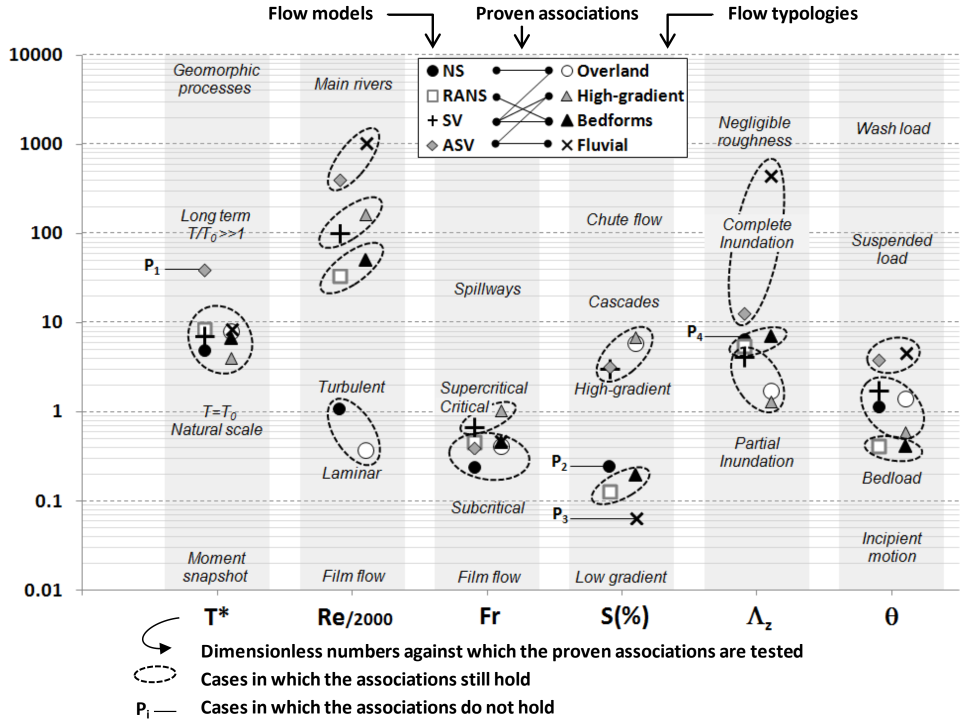
**Table 1 - Six textbook cases representing an approximate envelope of all the tested cases in the L-T plane of Fig.2, where L is the spatial scale (length of the flow domain) and T the temporal scale (duration of the process studied). Spatiotemporal scales are the determinants of modelling choices discussed in Section 3.1. The additional influence of flow typology and dimensionless numbers are discussed in Sections 3.2 and 3.3.**

The added paragraph is:

*"To take a few examples and guide the reader through the arguments and the figures of this paper, Table 1 gathers the information available for the six textbook cases outlined by sketches A to F in Fig.2. The selected studies represent a wide variety of cases (drawing an approximate envelop of cases in the L-T plane of Fig.2) followed in the forthcoming stages of the analysis and associated figures in Section 3.1.2 (determinants of modelling choices in the L-H plane, Fig.3), Section 3.2 (determinants sought in flow typology, Fig.6a and 7a) and Section 3.3 (determinants sought in the values of dimensionless numbers attached to the flow)." (L507-513)*

- In particular, the last figure of the paper is the most interesting result of the entire manuscript, and I suggest the authors to expand the description/comment on this very interesting result. I do not think the interpretation of this plot is trivial at all, so I believe its significance should be better emphasized in the paper text.

R: We agree. However, instead adding more elements in the text, we opted for some modifications of the old Fig.9 (now Fig.10, L865) to make it more self-explanatory, keeping its legend unchanged.



I do not have other specific comments, as the paper seems to be very accurate. The Figures are of good quality, referencing is appropriate and the discussion is clear and concise. Therefore, I congratulate the authors for the overall quality of the manuscript.

R: Thank you.

## Response to Reviewer #2

The paper presents an interesting attempt to draw links between different modelling approaches and to find appropriate time and length scales for different types of models. The approach adopted in the paper intends to be a general approach considering very different types of flows, from runoff to flows in large rivers.

R: We thank Reviewer #2 for his positive comments. We totally agree with his comments, and in the revised version we will introduce responses to all points raised by Reviewer #2 as shown below.

However, it must be stressed that this generalization still remains in the field of hydrology, with a point of view that is not as general as it could be. In particular, the Navier-Stokes (NS) equations are mentioned, but without being considered in their general fluid mechanics framework. So, the NS model is presented as the most general one, which is certainly the case, but turbulence is not discussed. However, considering that the flow velocity is the sum of a mean velocity and a fluctuating component, the NS equations can be solved to resolve as many as possible of the turbulence scales in DNS type simulations, also in flows with significant water depths. These DNS simulations are not discussed here, and NS models always appear in the “runoff” range of applications, which is quite limiting. Of course, if one remembers that the general review concerns hydrological modelling, then it becomes acceptable. But if this is the intention of the authors, then it should be stated much more clearly in the objectives of the paper.

R: The paper is indeed turned towards applications in the field of hydraulics and hydrology. The word "hydrology" was mentioned in the title for disambiguation, especially for readers’ specialists in fluid mechanics who would expect the usual analytical framework. This "hydrological" option will be recalled for clarity, in one word or two, at several places in the introductory parts of the manuscript (abstract L21, introduction L85 and L142-143).

However, high-precision hydraulics (for example) requires the NS models and may involve various (turbulence) scales and flow structures. We have thus followed the recommendation to mention the possible context-dependent strategies (DNS, LES, RANS) to solve these equations, which hopefully restore a bit more genericity. An additional comment will be added (L196-205).

*“There are many turbulence models (e.g. DNS-Direct Numerical Simulations, LES-Large Eddy Simulations and RANS-Reynolds-Averaged Navier-Stokes) suitable for free-surface flow modelling (Katopodes & Bradford 1999). Direct Numerical Simulations explicitly resolve all turbulence scales at the cost of more than $Re^3$ calculations (Härtel 1996) while Large Eddy Simulations (Smagorinsky 1963, Leonard 1974) filter out the smallest scales and resolve only the larger ones. The RANS equations (Smith & McLean 1977, Rödi 1988) do not resolve any scale but the stress terms used for their closure have proven useful for the modelling of near-bed turbulent patterns (see next subsection). The general trend is that improvements in efficiency of the algorithms have approximately kept pace with exponential improvements in computer power over the past 50 years (Moore 1965, Mavriplis 1998, Koomey et al. 2010) which tends to push the limitations of DNS and LES further away.”*

In a similar way, it then appears quite strange to read the word “turbulence” only when RANS models are discussed.

R: The term will be added L159, Section 2.1.1: "*(RANS: Reynolds 1895, for turbulent flows)*"

Indeed, RANS models were developed because performing DNS simulations to resolve all turbulence scales is impossible in practice due to excessive computational cost. Current research tends to push this limitation of NS still further away because of increasing available computational power using e.g. parallel computing. This is also an issue that deserves to be discussed.

R: These points will be mentioned L196-200.

*“There are many turbulence models (e.g. DNS-Direct Numerical Simulations, LES-Large Eddy Simulations and RANS-Reynolds-Averaged Navier-Stokes) suitable for free-surface flow modelling (Katopodes & Bradford 1999). Direct Numerical Simulations explicitly resolve all turbulence scales at the cost of more than* $Re^3$ *calculations (Härtel 1996) while Large Eddy Simulations (Smagorinsky 1963, Leonard 1974) filter out the smallest scales and resolve only the larger ones."*

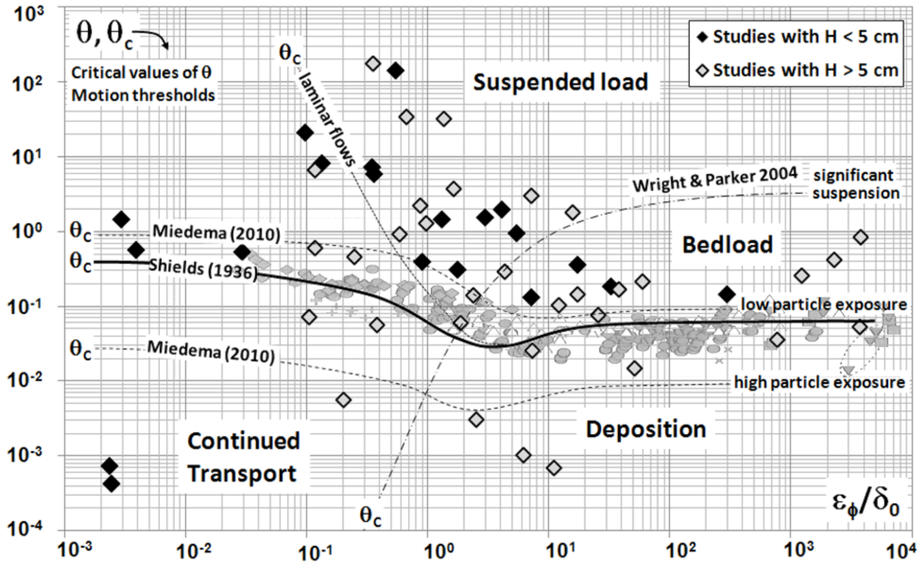
On the way erosion processes are handled, there can also be some debate. The references used by the authors are certainly pertinent in the field. However, the attempt of classifying the different approaches for erosion and grain movement at the same level as the NS, RANS, SV and ASV models is questionable. The distinction is not so clear, and a different classification, not directly linked to the flow models, but rather to the type of grain movement considered would maybe have been more appropriate.

R: We agree that erosion issues are not fully addressed with such a "parallel" strategy in terms of decreasing model refinements, which only provides a trend. Section 2.1.2 will be modified to clarify this point (L168-175) and to indicate that complementary indications on the determinants of modelling choices regarding erosion will be found in Section 3.

"*or at the scale of the erodible bed asperities. On the one hand, this advocates the examination of erosion issues from the angle of decreasing refinements of the "flow and erosion" models seen as a whole (e.g. expecting the most complicated erosion processes to be out of reach of the simplest combined models). On the other hand, there might be a certain disconnection between the refinement of the flow model and that of the chosen friction and erosion models, so the determinants of modelling choices should also be sought elsewhere: in flow typologies dictated by friction and flow retardation processes but also in "erosion types", seen through a dimensionless descriptor (Section 3).*"

These new lines (L168-175) mention a dimensionless descriptor for erosion (which will be the Shields number) which refers to phenomenologies that are not directly related to the NS, RANS, SV or ASV level, but rather to friction, bedforms and flow retardation processes as "proxys" for particle pick-up. What we intend to do is to introduce a new figure that shows a generalized Shields diagram. This would first offer an alternative to the reasoning in terms of refinement levels and second explicitly refer to the different erosion-transportation-deposition modes. This new Fig.9 comes at the end of Section 3.3.1 and is introduced by modifications in the text L826-834.

" *This number seems appropriate for most erosion issues because it has been widely applied and debated in the literature (Coleman 1967, Ikeda 1982, Wiberg & Smith 1987, Zanke 2003, Lamb et al. 2008) and also because of its numerous possible adaptations (Neill 1968, Ouriémi et al. 2007, Miedema 2010) to various flow typologies and non-uniform or poorly-known bed conditions. An impressive review on the use of the Shields number to determine incipient motion conditions, over eight decades of experimental studies, may be found in Buffington & Montgomery (1997). Finally, Fig.9 provides a generalized Shields diagram that includes motion threshold criteria under the effects of high or low particle exposure (Miedema 2010) or for laminar flows, also indicating the conditions of significant suspension (Wright & Parker 2004).*"



**Mis en forme :** Police :(Par défaut) Arial, Couleur de police : Bleu

**Figure 9 - Generalized dimensionless Shields diagram that summarizes the conditions and regimes of sediment transport or deposition, from the relative values of the Shields parameter ($\theta$) and incipient motion criterion ($\theta_c$). The X-axis bears the values of the ratio of particle size ($\varepsilon_\phi$) on the depth of the laminar sublayer ($\delta_0$). The diamonds refer to the studies cited in Appendix A that deal with erosion issues: black diamonds for studies in which flow depth is H<5 cm, grey diamonds otherwise. Data in the background show the critical $\theta_c$ values reported in the wide Buffington & Montgomery (1993) review of incipient motion conditions for varied flow regimes, particle forms and exposures.**

In particular, the authors mention that the SV framework offers a wide field for innovative research about sediment transport, which is certainly the case. But in these recent researches, many different types of sediment transport models are considered, depending also on the necessary level of simplification of the reality that is required. Indeed, the detailed composition of the soli to be eroded is not always known, or it is not possible to include that level of detail in the representation. So it is necessary to resort to averaging concepts, such as a representative grain diameter, then some factors to account for the non-uniformity of the grain-size distribution.

R: This is now explicitly mentioned in the responses to the previous comments.

The concentration of sediment in the flow could also be discussed: debris flows or mud flows are not handled in the same way as clear-water flows with sediment transport, and this distinction does not really appear here.

R: We fully agree again and your request incites us to reintroduce several elements that we had previously discarded from our working versions (as the Shields diagram) in an attempt to make the manuscript shorter.

In the discussion paper, we only mentioned hyperconcentrated flows and stratification (i.e. density) effects for sediment laden flows, not really addressing the effect of flow density (water+sediments mixture) on modelling options.

As far as we know, the trend is to use higher-level models when the water-sediment couplings become stronger. Again, the SV level allows many adaptations and strategies, but we feel there was a lack regarding the applications of the NS and RANS to dense, debris or avalanche flows, for example. A few lines on the subject were already present in Sections 2.2.2 and 2.4.2 but we will add some more literature elements in Section 2.2.2. (L216-220)

*“Such couplings may be sorted by increasing sediment loads, from dispersed multiphase flows (Parker & Coleman 1986, Davies et al. 1997) to density currents (Parker et al. 1986), hyperconcentrated flows (Mulder & Alexander 2001) and up to debris flows (e.g. Bouchut et al. 2003, Bouchut & Westdickenberg 2004), the latter derived as mathematical generalizations of the well-known Savage & Hütter (1989, 1991) avalanche models over explicit, pronounced topographies.”*

Minor comments and detailed suggestions for improvement will be submitted later as an attached file.

R: Thank you.

However, it must be stressed that this generalization still remains in the field of hydrology, with a point of view that is not as general as it could be.

R: Let us return to this phrase in the second comment of Reviewer#2 which pushed us to reconsider the conclusion of the paper, thus to formulate its concluding message in a quite different way. First, we split the conclusion in two and the previously existing part becomes Section 4.1 "Outcomes of this review" (L880). Second, the added part is Section 4.2 "Research challenges in hydrology and philosophy of modelling" (L957-1021) including a new Fig.11 that summarizes what has been done and what should be done in complement. Figure 11 finds itself at the tilting point between Sections 4.1 and 4.2.

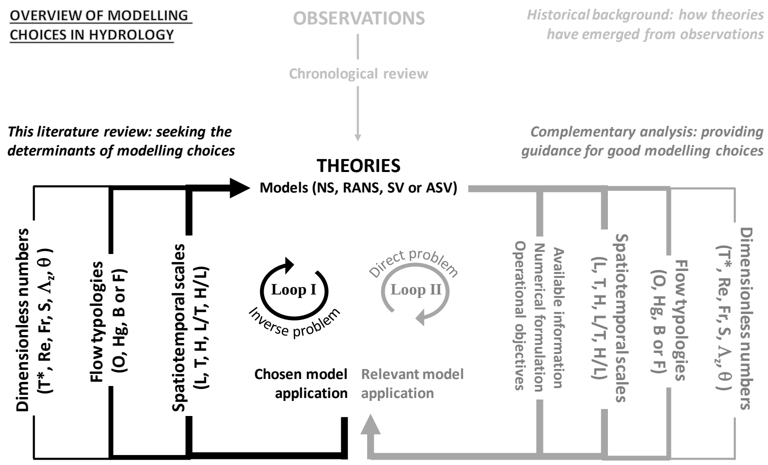


**Figure 11 – This figure provides a simplified overview of the available modelling choices in hydrology, in three distinct colours associated with specific research purposes or disciplines, showing the position of the present review relative to the others. The pale grey section aims at understanding how the available flow models have emerged from observations and early formulations of the flow equations, focusing on their conditions of validity i.e. the successive hypotheses made during their derivation. The black section recalls the procedure followed in this review paper (Loop I, "inverse problem"). Literature sources are processed through a procedure that analyses how the spatiotemporal scales (spatial scale L, time scale T, flow depth H, L/T and H/L ratios), then flow typology (Overland O, High-gradient Hg, Bedforms B or Fluvial F) and dimensionless numbers (dimensionless period T*, Reynolds number Re, Froude number Fr, bed slope S, inundation ratio $\square_z$, Shields parameter □) determine the choice of a flow model (Navier-Stokes NS, Reynolds-Averaged Navier-Stokes RANS, Saint-Venant SV or approximations ASV). Suggested in medium grey on the right are the scope and principles of future research challenges that would address the “*what should be done?”* (Loop II, "direct problem") question in echo to the current “*what has been done?*”concern (Loop I).**

On the one hand, the added section 4.2 discusses pending challenges and possible approaches quite specific to the fields of hydrology and hydraulics. On the other hand, it reintroduces very generic concepts and decision rules (hence the title "philosophy of modelling") in suggesting to select the approaches that respect the principle of parsimony.

*"This review has sought the determinants of modelling choices in hydrology (Figure 11, Loop I) from the basis provided by literature sources, without any intention to provide recommendations. However, for most practical applications, the starting point is the definition of a scope and the endpoint is the evaluation of the objective function to evaluate the success or the failure of the chosen modelling strategy. A question thus arises on how to guide the modeller in the choice of an adequate model, in function of given, approximately known spatiotemporal scales, flow typology and dimensionless numbers (Figure 11, Loop II). According to the principle of parsimony, modellers should seek the simplest modelling strategy capable of (i) a realistic representation of the physical processes, (ii) matching the performances of more complex models and (iii) providing the right answers for the right reasons.*

*- (i) Throughout the last decades, an important change of the scope of free-surface flow modelling applications has taken place, with subsequent changes in the objective functions resorted to. The development of hydrological and hydraulic sciences has been directly linked to the progresses in understanding processes, in theoretical model development (e.g. computational facilities: numerical techniques, data assimilation, thorough model exploration, inverse calculus) and in data acquisition (new devices, remote sensing, LiDAR). "It may seem strange to end a review of modelling with an observation that future progress is very strongly linked to the acquisition of new data and to new experimental work but that, in our opinion, is the state of the science" (Hornberger & Boyer 1995).*

*- (ii) However, there remains an important need for research on classical free-surface flow (hydrological or hydraulic) modelling for engineering applications in predicting floods, designing water supply infrastructures and for water resources management, from the headwater catchment to the regional scale. More recently, free-surface flow modelling has become an indispensable tool for many interdisciplinary projects, such as predicting pollution and/or erosion incidents, the impact of anthropogenic and climate change on environmental variables such as water, soil, biology, ecology, or socio-economy and ecosystemic services. The direct consequence is a significant increase of the complexity of the objective function, from simple mono-site (e.g. one-point), mono-variable (e.g. the water depth) and mono-criterion (e.g. the error on peakflow) to complex multi-site (e.g. large number of points within a catchment), multi-variable (e.g. water depth, hydrograph, water table, concentrations,*

*ecological indicators, economic impact) and multi-criteria (e.g. errors on peakflow, volume, RMSE) objective functions.*

*- (iii) There is often a mismatch between model types, site data and objective functions. First, models were developed independently from the specificities of the study site and available data, prior to the definition of any objective function. In using free-surface flow models, the context of their original purpose and development is often lost, so that they may be applied to situations beyond their validity or capabilities. Second, site data are often collected independently of the objectives of the study. Third, the objective function must be specific to the application but also meet standard practices in evaluating model performance, in order to compare modelling results between sites and to communicate the results to other scientists or stakeholders. The known danger is to use flow and erosion equations outside their domains of validity (i.e., breaking the assumptions made during their derivation) then to rely on the calibration of model parameters as for technical compensations of theoretical flaws, at the risk of losing the physical sense of model parameters, creating equifinality and obtaining the "right results for the wrong reason" (Klemeš 1986). Choosing the right model for the right reason is crucial but the identification of the optimal data-model couple to reach a predefined objective is not straightforward. We need a framework to seek the optimum balance between the model, data and the objective function as a solution for a hydrological or hydraulic problem, on the basis of the principle of parsimony. The latter follows a famous quote often attributed to Einstein, that "everything should be made as simple as possible, but not simpler" which somehow originates in the philosophy of William of Ockham (1317) (Numquam ponenda est pluralitas sine necessitate [Plurality must never be posited without necessity]) or may even be traced back to Aristotle's (~350 BCE) Analytica Posteriora that already advocated demonstrations relying on the fewest possible number of conjectures, i.e. the dominant determinisms.*

*Finally, analytical procedures for free-surface flows and erosion issues necessitates a comprehensive analysis of the interplay between models (assumptions, accuracy, validity), data requirements and all contextual information available, encompassed in the "signature" of any given application: model refinement, spatiotemporal scales, flow typology and scale-independent description by dimensionless numbers. This review helps the modeller positioning his (or her) case study with respect to the modelling practices most encountered in the literature, without providing any recommendation. A complementary step and future research challenge is to decipher relevant modelling strategies from the available theoretical and practical material, resorting to the same objects, the previously defined signatures. Its purpose clearly is to address the "which model, for which scales and objectives?" question. A complete analytical framework, comprised of both loops, would provide references and guidelines for modelling strategies. Its normative structure in classifying theoretical knowledge (the mathematics world, equations and models) and contextual descriptions (real-life physical processes, scales and typologies) hopefully makes it also relevant for other Earth Sciences."*

## Additional references

Bouchut, F., Mangeney-Castelnau, A., Perthame, B., Vilotte, J.-P. (2003). A new model of Saint-Venant and Savage-Hutter type for gravity driven shallow water flows, Comptes-Rendus de l'Académie des Sciences de Paris, 336, pp.531-536.

Bouchut, F. and Westdickenberg, M. (2004). Gravity-driven shallow water models for arbitrary topography, Communications in Mathematical Sciences, 2, pp.359-389.Härtel, C. (1996). Turbulent flows: direct numerical simulation and large-eddy simulation, In: Handbook of Computational Fluid Mechanics, R. Peyret Ed., Elsevier, New York, pp.283-338.

Katopodes, N. D. and Bradford, S. F. (1999). Mechanics of overland flow, Proceedings of the International Workshop on Numerical Modelling of Hydrodynamic Systems, Zaragoza, Spain, 21-24 June 1999.

Klemes, V. (1986). Dilletantism in hydrology: Transition or destiny?, Water Resources Research, 22, pp.177-188.

Koomey, J., Berard, S., Sanchez, M. and Wong, H. (2010). Implications of historical trends in the electrical efficiency of computing, IEEE Annals of the history of computing, 33 (3), pp.46-54.

Leonard, A. (1974). Energy cascade in large-eddy simulation of turbulent channel flow, Advances in Geophysics, 18, pp.237-248.

Mavriplis, D. (1998). On Convergence Acceleration Techniques for Unstructured Meshes. Technical Report ICASE No. 98-44 and NASA/CR-1998-208732, Institute for Computer Applications in Science and Engineering, NASA Langley Research Center.

Moore, G. E. (1965). Cramming More Components onto Integrated Circuits, Electronics, pp. 114–117.

Rödi, W. (1988). Turbulence models and their application in hydraulics - a state of the art review, International Association for Hydraulic Research, Delft, The Netherlands, 47p.

Savage, S. B. and Hutter, K. (1989). The motion of a finite mass of granular material down a rough incline, Journal of Fluid Mechanics, 199, pp.177-215.

Savage, S. B. and Hutter, K. (1991). The dynamics of avalanches of granular materials from initiation to runout. Part I: Analysis, Acta Mechanica, 86, pp.201-223.

Smagorinsky, J. (1963). General circulation experiments with the primitive equations, Monthly Weather Review, 91 (3), pp.99-164.

Wright, S. and Parker, G. (2004). Flow Resistance and Suspended Load in Sand-Bed Rivers: Simplified Stratification Model, Journal of Hydraulic Engineering, 130 (8), pp.796-805.

# Determinants of modelling choices for 1-D free-surface flow and erosion issues in hydrology: a review

Bruno Cheviron[a], Roger Moussa[b]

[a] IRSTEA, UMR G-EAU "Gestion de l'Eau, Acteurs et Usages", 361 rue Jean-François Breton, BP 5095, 34196 Montpellier Cedex 5, France.

bruno.cheviron@irstea.fr

[b] INRA, UMR LISAH, "Laboratoire d'étude des Interactions entre Sol - Agrosystème - Hydrosystème", 2 Place Pierre Viala, 34060 Montpellier Cedex 1, France.

moussa@supagro.inra.fr

## Abstract

This review paper investigates the determinants of modelling choices, for numerous applications of 1-D free-surface flow and erosion equations in hydrology, across multiple spatiotemporal scales. We aim to characterize each case study by its signature composed of model refinement (Navier-Stokes: NS, Reynolds-Averaged Navier-Stokes: RANS, Saint-Venant: SV or Approximations of Saint-Venant: ASV), spatiotemporal scales (domain length: L from 1 cm to 1000 km; temporal scale: T from 1 second to 1 year; Flow depth: H from 1 mm to 10 m), flow typology (Overland: O, High gradient: Hg, Bedforms: B, Fluvial: F) and dimensionless numbers (Dimensionless time period T*, Reynolds number Re, Froude number Fr, Slope S, Inundation ratio $\Lambda_z$, Shields number $\theta$). The determinants of modelling choices are therefore sought in the interplay between flow characteristics, cross-scale and scale-independent views. The influence of spatiotemporal scales on modelling choices is first quantified through the expected correlation between increasing scales and decreasing model refinements, identifying then flow typology a secondary but mattering determinant in the choice of model refinement. This finding is confirmed by the discriminating values of several dimensionless numbers, that prove preferential associations between model refinements and flow typologies. This review is intended to help each modeller positioning his (her) choices with respect to the most frequent practices, within a generic, normative procedure possibly enriched by the community for a larger, comprehensive and updated image of modelling strategies.

## Keywords

Free-surface flow, modelling strategy, cross-scale analysis, flow typology, dimensionless numbers.

## Summary

## 1 Introduction

Free-surface flow models cover a wide range of environmental and engineering applications, across multiple spatiotemporal scales, through successive flow aggregations over various bed topographies: these govern both the qualitative (flow typology) and quantitative (dimensionless numbers) flow characteristics. Each case study may thus be positioned along "streamwise scenarios" (from runoff initiation to the main rivers) from unequivocal indications of the spatiotemporal scales, flow typology and associated dimensionless numbers. This literature review investigates the determinants of choices made for 1-D free-surface flow and erosion modelling in hydrology, seeking links between contextual information (spatiotemporal scales, flow typologies, dimensionless numbers) and conceptual descriptions (refinement of the flow equations or, equivalently, richness of the physical basis). The entire set of descriptors, i.e. model refinement, spatiotemporal scales, flow typology and dimensionless numbers, constitutes the signature of a study, which is the open normative procedure designed to allow comparisons between studies and to be fed by the community.

For the sake of genericity, this review addresses a wide range of spatiotemporal scales, starting at the smallest plot scales (spatial scale: domain length L<10 m; time scale: duration of the process T<10 s; flow depth: H<1 cm, Fig. 1), those of runoff genesis, overland flow hydraulics and detailed particle-scale physics (Horton 1945, Emmett 1970, Feng & Michaelides 2002, Schmeeckle & Nelson 2003). The intermediate scales of catchment and hillslope processes are these expected to exhibit the widest variety of flow typologies thus modelling strategies (Croke & Mockler 2001, Parsons et al. 2003, Aksoy & Kavvas 2005). The larger river basin scales (L>100 km; T>10 days; H>1 m) are also handled here, relevant for river flow modelling, flood prediction and water resources management (Nash & Sutcliffe 1970, Rosgen 1994, Loucks & van Beek 2005) with regional surface-subsurface interactions (De Marsily 1986), non-point pollution, fluvial sediment budgets and global biogeochemical cycles (Walling 1983, Milliman & Syvitski 1992, Syvitski & Milliman 2007).

On the Earth's surface, flow aggregation in the streamwise direction occurs across several geomorphic thresholds (Kirkby 1980, Milliman & Sivitsky 1992, Church 2002, Paola et al. 2009), through a succession of flow typologies (Emmett 1970, Grant et al. 1990, Rosgen 1994, Montgomery & Buffington 1997). Flow aggregation in space and time is described, through the width function and geomorphological unit hydrograph concepts (Kirkby 1976,  Robinson et al. 1995, Agnese et al. 1998), under the angle of connecting-scale hydrological and sedimentological pathways (see the review by Bracken et al. 2013) or debating the merits of similitude laws versus upscaling issues in the description of hydrological processes (Strahler 1956, Blöschl and Sivapalan 1995, Slaymaker 2006). An alternative consists in examining the scale matching between available data and modelling aims (Lilburne 2002). This raises technical (contextual) as well as strategic (conceptual) issues, handled here from an overview on the most popular modelling practices, confronting the theoretical refinement of flow models to the specific nominal scales of the processes at play.

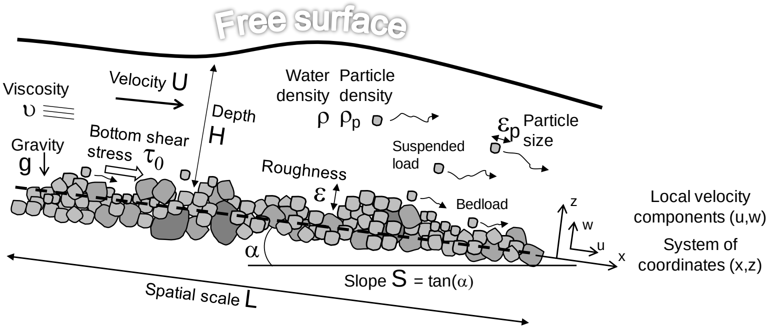


**Figure 1 - Quantities most often used in the literature of free-surface flow and erosion modelling, with explicit reference to the (L, T, H) spatiotemporal scales of interest. This review is limited to 1D (x) spatial representations for simplicity, focusing on the streamwise (x) component of the mass and momentum conservation equations. The streamwise length (L) and velocity (U) suggest a natural time scale $T_0$=L/U for the propagation of information, waves or perturbations, to be compared with the time scales (T) opted for in the literature.**

Many papers or handbooks have summarised free-surface flow modelling and numerical techniques in hydraulics (King & Brater 1963, Abbott 1979, Cunge et al. 1980, Carlier 1980, French 1985) or hydrology (Chow 1959, Kirkby 1978, Beven 2000) for various contexts, purposes and flow typologies. Less works have discussed the concern of *ad hoc* friction laws (Leopold et al. 1960, Gerbeau & Perthame 2001, Nikora et al. 2001, Roche 2006, Burguete et al. 2008), at the microscopic or macroscopic scales (Richardson 1973, Jansons 1988, Priezjev & Troian 2006, Smith et al. 2007, Powell 2014) although friction, flow retardation and energy dissipation processes are closely related to bedforms, thus plausibly govern flow typologies then, possibly, modelling choices. Often outside any focus on friction, numerous works have provided wide overviews on erosion modelling (Ritchie & McHenry 1990, Laflen et al. 1991, Merritt et al. 2003, Aksoy and Kavvas 2005, Boardman 2006). Erosion models that lean on the most sophisticated flow models calculate explicit particle detachment, transport and deposition from velocity fields  or flow energetics (Vanoni 1946, Hino 1963, Lyn et al. 1992, Mendoza & Zhou 1997) while reduced complexity models either assume the "transport capacity" (Foster & Meyer 1972, Bennett 1974) or "transport distance" schools of thoughts (see details in Wainwright et al. 2008).

This multidisciplinary review (hydrology, hydraulics, fluid mechanics and erosion science) searches for the determinants of modelling choices. It focuses on hydrology but borrows from hydraulics and fluid mechanics, also when addressing erosion issues. The methodology consists in defining the “signature” of each case study as the chosen model refinement and the given flow typology, spatiotemporal scales and dimensionless numbers, hypothesizing the conceptual element (model refinement) is the consequence of the contextual elements. The paper is organized as follows: section 2 sorts the flow equations into four levels of refinement, section 3 plots these refinements versus the spatiotemporal scales of the studies, also depicting the influence of flow typologies and dimensionless numbers. Section 4 discusses the results and future research leads. Some of the best documented references among the cited literature have been gathered in Appendix A: most figures in this manuscript were plotted from this database.

# 2 Flow models

## 2.1 List of flow models

### 2.1.1 Water flow

Free-surface flow equations in the literature may roughly be sorted into four levels of decreasing refinement, from the richness of their physical basis. The choice made here includes the Navier-Stokes equations (noted NS: Navier 1822, Stokes 1845), their average in time termed Reynolds-Averaged Navier-Stokes equations (RANS: Reynolds 1895, for turbulent flows), the depth-averaged Saint-Venant equations (SV: Saint-Venant 1871) and further approximations (referred to as ASV), among which the Diffusive Wave (DWE: Hayami 1951) and Kinematic Wave Equations (KWE: Iwagaki 1955, Lighthill & Whitham 1955).

### 2.1.2 Erosion

The associated erosion equations (not shown) are based on a representation of detachment and transport on hillslopes (Bennett 1974, Van Rijn 1984a, b, Wainwright et al. 2008), in streams (Einstein 1950) or through the channel network (Du Boys 1879, Exner 1925, Hjulström 1935, Shields 1936, Bagnold 1956). Friction is the link between water flow and erosion issues in terms of physical processes at play at the particle scale, or at the scale of the erodible bed asperities. On the one hand, this advocates the examination of erosion issues from the angle of decreasing refinements of the "flow and erosion" models seen as a whole (e.g. expecting the most complicated erosion processes to be out of reach of the simplest combined models). On the other hand, there might be a certain disconnection between the refinement of the flow model and that of the chosen friction and erosion models, so the determinants of modelling choices should also be sought elsewhere: in flow typologies dictated by friction and flow retardation processes but also in "erosion types", seen through a dimensionless descriptor (Section 3). ~~However, the scope here is not to review the choices made for friction~~

~~modelling; friction phenomena, with the associated flow retardation and energy dissipation processes, are rather considered for their influence on flow typologies, as discussed later in the manuscript.~~

## 2.2 Navier-Stokes

### 2.2.1 Water flow

The Navier-Stokes (NS) equations have suitable simplifications for the shallow water cases (L>>H) commonly used to describe free-surface flows. The three-dimensional fluid motion problem is reduced here to a two-dimensional description, whose projection along the streamwise axis writes:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} + \frac{1}{\rho}\frac{\partial p}{\partial x} = g_x + \frac{1}{\rho}\frac{\partial \tau}{\partial x} \tag{1}$$

where $x$ is the longitudinal distance [L], $z$ the vertical coordinate [L], $t$ is time [T], $u$ is the local water velocity in $x$ [$LT^{-1}$], $\rho$ is water density [$ML^{-3}$], $g_x$ is the projection of gravity $g$ on $x$ [$LT^{-2}$] and $\tau$ is the tangential stress due to water [$ML^{-1}T^{-2}$] noted $\tau_0$ on the bed in Fig. 1.

The Navier-Stokes equations stay valid throughout the full range of flow regimes, scales and contexts. They are preferentially used where much complexity is needed, often when relevant simplified flow descriptions could not be derived, for example for particle-scale applications (Chen & Wu 2000, Wu & Lee 2001, Feng & Michaelides 2002), overland flow (Dunkerley 2003, 2004) or flows over pronounced bedforms (Booker et al. 2001, Schmeeckle & Nelson 2003). A very wide review of numerical methods and applications for the NS equations is provided by Gresho & Sani (1998) and a benchmark of numerous solvers by Turek (1999).

There are many turbulence models (e.g. DNS-Direct Numerical Simulations, LES-Large Eddy Simulations and RANS-Reynolds-Averaged Navier-Stokes) suitable for free-surface flow modelling (Katopodes & Bradford 1999). Direct Numerical Simulations explicitly resolve all turbulence scales at the cost of more than $Re^3$ calculations (Härtel 1996) while Large Eddy Simulations (Smagorinsky

1963, Leonard 1974) filter out the smallest scales and resolve only the larger ones. The RANS equations (Smith & McLean 1977, Rödi 1988) do not resolve any scale but the stress terms used for their closure have proven useful for the modelling of near-bed turbulent patterns (see next subsection). The general trend is that improvements in efficiency of the algorithms have approximately kept pace with exponential improvements in computer power over the past 50 years (Moore 1965, Mavriplis 1998, Koomey et al. 2010) which tends to push the limitations of DNS and LES further away.

### *2.2.2 Erosion*

Several types of practical applications dictate the use of high-level formalisms in the description of particle detachment and transport, typically to handle explicit bed geometries and alterations, for example jet scours and regressive erosion (Stein et al. 1993, Bennett et al. 2000, Alonso et al. 2002), diverging sediment fluxes in canals (Belaud & Paquier 2001) or incipient motion conditions, calculated from grain size, shape and weight (Stevenson et al. 2002). The NS formalism is also needed to describe strong water-sediment, i.e. couplings in which the solid phase exerts an influence on the liquid phase, acting upon velocity fields, flow rheology and erosive properties (Sundaresan et al. 2003)~~, Parker & Coleman 1986, Parker et al. 1986, Davies et al. 1997, Mulder & Alexander 2001)~~. Such couplings may be sorted by increasing sediment loads, from dispersed multiphase flows (Parker & Coleman 1986, Davies et al. 1997) to density currents (Parker et al. 1986), hyperconcentrated flows (Mulder & Alexander 2001) and up to debris flows (Bouchut et al. 2003, Bouchut & Westdickenberg 2004), the latter derived as mathematical generalisations of the well-known Savage & Hütter (1989, 1991) avalanche models over explicit, pronounced topographies. Moreover, the NS formalism offers the possibility to work on the energy equations: the erosive power and transport capacity of sediment-laden flows may be estimated from the energy of the flow, debating the case of turbulence damping (or not) with increasing sediment loads (Vanoni 1946, Hino 1963, Lyn et al. 1992, Mendoza & Zhou 1997). The matter is not free from doubt today (Kneller & Buckee 2001) and frictional drag, abrasion due to impacts of the travelling particles and increased flow viscosity have been described prone to enhance the detachment capacities of loaded flows (Alavian et al. 1992, Garcia & Parker 1993).

## *2.3 Reynolds-Averaged Navier-Stokes*

### *2.3.1 Water flow*

The Reynolds-Averaged Navier–Stokes (RANS) equations are a turbulence model, using time-averaged equations of fluid motion, less generic than the NS formalism. The hypothesis behind these equations is that instantaneous pressure and velocities may be decomposed into time-averaged and randomly fluctuating turbulent parts, which finally yields:

$$\frac{\partial \overline{u}}{\partial t} + \overline{u}\frac{\partial \overline{u}}{\partial x} + \overline{w}\frac{\partial \overline{u}}{\partial z} + g\frac{\partial H}{\partial x} = gS + \frac{1}{\rho}\frac{\partial \tau}{\partial z} \qquad (2)$$

where $\overline{u}$ [LT$^{-1}$] and $\overline{w}$ [LT$^{-1}$] are the time-averaged local water velocities in x and z, H is the flow depth [L] and S is the bed slope [-].

In this formulation, the "Reynolds stress" term $\tau$ is of crucial importance for free-surface flow, friction and erosion modelling, especially for shallow flows, first because it is the closure term ( $\tau = -\rho\, \overline{u'w'}$ ) and second because the Reynolds stresses have been closely related, in magnitude and direction, to the size and arrangement of bed asperities. The combined analysis of the relative magnitude of the u' and w' terms has become the purpose of "quadrant analysis" (Kline et al. 1967, Raupach 1981, Kim et al. 1987) that identifies the four cases of outward interactions (quadrant I: u'>0, w'>0), ejections (quadrant II: u'<0, w'>0), inward interactions (quadrant III: u'<0, w'<0) and sweeps (quadrant IV: u'>0, w'<0). Depending on the submergence and geometry of bed asperities, the maximal Reynolds stresses, those with significant effects on flow structure, have most often been reported to occur near or just above the roughness crests (see Nikora et al. 2001, Pokrajac et al. 2007 and the review by Lamb et al. 2008a).

### 2.3.2 Erosion

In their paper on movable river beds, Engelund & Fredsoe (1976) judiciously reformulated and exploited the existing hypotheses (Einstein & Banks 1950, Bagnold 1954, Fernandez Luque & van Beek 1976) of a partition between “tractive” destabilizing shear stresses and “dispersive” equalizing drags. The vertical concentration profiles of bedload and suspended load were calculated from incipient sediment motion conditions, relating stresses on the particles to the values and variations of near-bed velocities. One step further, the physical explanation, mathematical definition, point of application, main direction and erosive efficiency of the turbulent near-bed stresses have become private hunting grounds of the RANS models throughout the years (Nikora et al. 2001, Nino et al. 2003).

The maximal Reynolds stresses are located near the crests of the submerged bed asperities, where turbulent velocity fluctuations reach several times the average near-bed velocity values, which greatly enhances particle detachment (Raupach et al. 1991, Nikora & Goring 2000, Lamb et al. 2008a). Very few studies deal with the magnitude and point of application of the Reynolds stresses for partial inundation cases (Bayazit 1976, Dittrich & Koll 1997, Carollo et al. 2005) although turbulent flows between emergent obstacles often occur in natural settings. Particle detachment is generally attributed to “sweeps” (quadrant IV: u’>0, w’<0) (Sutherland 1967, Drake et al. 1988, Best 1992) or “outward interactions” (u’>0, w’>0) (Nelson et al. 1995, Papanicolaou et al. 2001) but depends on bed geometries and bed packing conditions. Finally, the RANS equations allow explicit calculations of shear stresses and particle-scale pick-up forces, thus incipient motion conditions (Nino et al. 2003, Afzalimehr et al. 2007). They may handle the movements of detached particles in weak transportation stages (Bounvilay 2003, Julien & Bounvilay 2013) down to near-laminar regimes (Charru et al. 2004).

## 2.4 Saint-Venant

### 2.4.1 Water flow

The Saint-Venant (SV) equations are obtained by depth-integrating the Navier–Stokes equations, neglecting thus the vertical velocities as well as vertical stratifications in the streamwise velocity (Stoker 1958, Johnson 1998, Whitham 1999). The integration process (Chow 1959, Abbott 1979) incorporates an explicit bottom friction term $\tau_0$ that previously appeared only as a boundary condition in the NS and RANS equation:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + g\frac{\partial H}{\partial x} = gS + \frac{\tau_0}{\rho H} \tag{3}$$

Recent attempts have been made in the field of fluid mechanics to derive specific expressions for $\tau_0$ (laminar flows: Gerbeau & Perthame 2001, macro-roughness: Roche 2006, thin flows: Devauchelle et al. 2007, turbulent flows: Marche 2007, multi-layer SV model: Audusse et al. 2008). However, the common practice in hydraulics and hydrology is rather to approximate steady-state equilibrium between bottom friction $\tau_0$ and the streamwise stress exerted at the bottom of a water column ($\tau_0=\rho gHS_f$) to reach the popular formulation:

$$\underbrace{\frac{\partial U}{\partial t}}_{(i)} + \underbrace{U\frac{\partial U}{\partial x}}_{(ii)} + \underbrace{g\frac{\partial H}{\partial x}}_{(iii)} = g\big(\underbrace{S}_{(iv)} - \underbrace{S_f}_{(v)}\big) \tag{4}$$

where (i) is the unsteadiness term, (ii) the convective acceleration term, (iii) the pressure gradient term, while (iv) and (v) form the diffusive wave approximation (later discussed).

In the above, $S_f$ (-) is the "friction slope" whose expression depends on flow velocity and on the chosen friction law, often one of the Chézy, Darcy-Weisbach or Manning formulations (e.g. $S_f$=$nU^2/8gH$ with Manning's n friction coefficient). The derivation of the SV equations by Boussinesq (1877) involved a momentum correction coefficient β [-] in the advection term (King & Brater 1963, Chen 1992) to account for stratification effects in the vertical distribution of velocities, especially plausible in sediment-laden flows or in presence of density currents.

The SV equations may account for flows of variable widths and depths, for example in floodplains (Bates & De Roo 2000, Beltaos et al. 2012), rivers (Guinot & Cappelaere 2009), overland flow (Berger & Stockstill 1995, Ghavasieh et al. 2006), overpressure in drainage systems (Henine et al. 2014), man-made channels (Zhou 1995, Sen & Garg 2002, Sau et al. 2010), vegetation flushing (Fovet et al. 2013), channel networks (Choi & Molinas 1993, Camacho & Lees 1999) or natural settings (Moussa & Bocquillon 1996a, Wang & Chen 2003, Roux & Dartus 2006, Burguete et al. 2008, Bates et al. 2010), including these with curved boundaries (Sivakumaran & Yevjevich 1987). Discharge and cross-sectional area may conveniently be used instead of velocity and water depth, and the two equations describing mass and momentum in the Saint-Venant system now write (Sivapalan et al. 1997):

$$\frac{\partial \mathrm{A}}{\partial \mathrm{t}} + \frac{\partial \mathrm{Q}}{\partial \mathrm{x}} = \mathrm{q_a} \tag{5}$$

$$\frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{1}{gA}\frac{\partial}{\partial x}\left(\beta\frac{Q^2}{A}\right) + \frac{\partial H}{\partial x} + S_f - S = 0 \tag{6}$$

where $A$ is the cross-sectional area [L²], $Q$ is the discharge [$\mathrm{L^3T^{-1}}$], $q_a$ is the lateral flow per unit channel length [$\mathrm{L^2T^{-1}}$]. The magnitudes of the various terms in equations (5) and (6) are given in the literature (e.g. Henderson 1966, Kuchment 1972).

### 2.4.2 Erosion

In the hydrology-erosion community, the SV level is that of the *Concepts of mathematical modelling of sediment yield* by Bennett (1974). This landmark paper extended Exner's (1925) conservation of sediment mass, adding the possibility to handle different fluid and particle velocities, also accounting for particle dispersion *via* a diffusion term. Unfortunately, most citing papers discard this term, taking particle velocity equal to water velocity. The assumption seems false if transport occurs as bedload or saltation load, questionable for suspended load trapped into turbulent motions, exact only for very small particles borne by laminar flows. Although warning against the capability of first-order laws to "*represent the response of sediment load to changes in transport and detachment capacity*" (Bennett 1974, p.491), the author recommended the use of such a model (Foster and Meyer 1972). The proposed simplification writes $e/D_c$=1-$c/T_c$, where the net erosion rate ($e$) is normalised by the maximal detachment capacity ($D_c$) while sediment load ($c$) is normalised by the maximal transport capacity of the flow ($T_c$). An additional (uncertain) hypothesis was that of maximal detachment capacity for minimal sediment load, *i.e.*, clear water. See the controversial comments around the Wainwright et al. (2008) paper: the areas of disagreement revolve around the ability of models to handle unsteady flow conditions, to deal with suspended and/or bedload transport, to consider particles of different sizes and to stay valid over realistic ranges of sediment concentration.

Those questions directly address the possibilities of SV-level approaches. Higher-level models (NS, RANS) better address the dynamics of incipient motion (Dey & Papanicolaou 2008), especially in shallow laminar flows (Charpin & Myers 2005) or focusing on granular flows (Parker 1978a, b, Charru et al. 2004, Charru 2006). Refined models are also needed to explicitly handle specific particle velocities (Bounvilay 2003), to describe particle diffusion in secondary currents (Sharifi et al. 2009), to account for the spatial heterogeneity of "neither laminar nor turbulent" overland flows (Lajeunesse et al. 2010) or to introduce modifications in flow rheology (Sundaresan et al. 2003). On the other hand, slope effects (Polyakov & Nearing 2003), particle-size effects (Van Rijn 1984a, Hairsine & Rose 1992a, Sander et al. 2007, Wainwright et al. 2008), flow stratification effects (van Maren 2007), the effects of hyperconcentrated flows (Hessel 2006) and the bedload transport (Van Rijn 1984b, Julien & Simmons 1985, Hairsine & Rose 1992b, Wainwright et al. 2008) have received much attention within the SV or ASV formalisms.

Whatever the liquid-solid coupling opted for, the SV level covers the widest variety of contexts, from overland erosion models (Simpson & Castelltort 2006, Nord & Esteves 2010) to dam-break hydraulics over erodible beds (Cao et al. 2004) and the analysis of channel inception driven by the variations of the Froude number (Izumi & Parker 1995) or the impact of travelling particles (Sklar & Dietrich 2004, Lamb et al. 2008b). Sediment detachment and transport over plane beds (Williams 1970), rough beds (Afzalimehr & Anctil 1999, 2000, Gao & Abrahams 2004), step-pools (Lamarre & Roy 2008) or pool-riffle sequences (Sear 1996, Rathburn & Wohl 2003) have yielded often-cited studies, while sediment flushing in reservoirs (Campisano et al. 2004) and vegetation flushing in canals (Fovet et al. 2013) constitute more specific applications. Cited limitations of the SV approaches are their inability to explicitly describe the near-bed velocity fluctuations, especially the local accelerations responsible for particle entrainment but also the vertical gradients of the streamwise velocity, for bedload transport in the laminar layer. This lack of accuracy in the description of flow characteristics also endangers the possibility to predict the formation, transformation and migration of geometrical bed patterns, which in turn requires the full set of 3D (x, y, z) NS equations in several cases (Lagrée 2003, Charru 2006, Devauchelle et al. 2010).

There seems to exist a dedicated "NS-SV Morphodynamics" research lead that uses rather simple bedload transport formulae (Du Boys 1890, Meyer-Peter & Müller 1948, Einstein & Banks 1950, Bagnold 1966, Yalin 1977) to calculate sediment fluxes from excess bed shear stresses, in studies of long-term system evolutions. These low "system evolution velocities" appear under the "quasi-static" flow hypothesis: particle velocity may be neglected before water velocity, which allows neglecting the unsteadiness term in the momentum equation but on no account in the continuity equation (Exner law) that describes bed modifications (Parker 1976). Moreover, shear stresses are generally calculated from near-bed laminar or near-laminar velocity profiles, sometimes with the regularising hypothesis that detachment and transport occur just above the criterion for incipient motion (see the review by Lajeunesse et al 2010). Various applications address rivers with mobile bed and banks (Parker 1978a, b), focus on self-channelling (Métivier & Meunier 2003, Mangeney et al. 2007) and often resort to formulations at complexity levels between these of the NS and the SV approaches (Devauchelle et al. 2007, Lobkovsky et al. 2008).

## 2.5 Approximations to Saint-Venant

### 2.5.1 Water flow

When the full Saint-Venant equations are not needed or impossible to apply due to a lack of data, an option is to neglect one or several terms of the momentum equation (Ponce and Simons 1977, Romanowicz et al. 1988, Moussa & Bocquillon 1996a, Moussa & Bocquillon 2000). In most practical applications for flood routing, the unsteadiness (i) and convective acceleration (ii) terms in (4) may be neglected, suppressing the first two terms from (6). Combining the remaining terms in (5) and (6), we obtain the Diffusive Wave equation (Moussa, 1996):

$$\frac{\partial Q}{\partial t} + C\left(\frac{\partial Q}{\partial x} - q_a\right) - D\left(\frac{\partial^2 Q}{\partial x^2} - \frac{\partial q_a}{\partial x}\right) = 0 \qquad (7)$$

where $C$ [$LT^{-1}$] and $D$ [$L^2T^{-1}$] are non-linear functions of the discharge $Q$ (and consequently the flow depth $H$) known as the celerity and diffusivity, respectively.

In cases where the pressure-gradient term (iii) in (4) can also be neglected, the third term of (6) also vanishes and the Diffusive Wave becomes the Kinematic Wave equation, with $D$=0 in (7). The Diffusive Wave (Cunge 1969, Akan & Yen 1981, Rutschmann & Hager 1996, Wang et al. 2006, Wang et al. 2014) can thus be considered a higher order approximation than the Kinematic Wave approximation (Katopodes 1982, Zoppou & O'Neill 1982, Daluz Vieira 1983, Ferrick 1985, Ponce 1990). Both have proven very useful for canal control algorithms (Rodellar et al. 1993) or flood routing procedures, with lateral inflow (Fan & Li 2006), in rectangular channels (Keskin & Agiralioglu 1997), for real time forecast (Todini & Bossi 1986), in lowland catchments (Tiemeyer et al. 2007), for small catchments (Moussa et al. 2002, Chahinian et al. 2005, Charlier et al. 2007), for mountainous catchments (Moussa et al. 2007) or tropical catchments (Charlier et al. 2009), at the largest scale of the Amazon basin (Trigg et al. 2009, Paiva et al. 2013), for anthropogenic hillslopes (Hallema & Moussa 2013), to address backwater effects (Munier et al. 2008), stormwater runoff on impervious surfaces (Blandford & Meadows 1990, Parsons et al. 1997), stream-aquifer interactions (Perkins & Koussis 1996) or volume and mass conservation issues (Perumal & Price 2013). Given their "nominal" scales of application, the ASV models are sometimes fed by airborne (remote sensing) data acquisition (Jain & Singh 2005, Reddy et al. 2007). In addition, predictive uncertainties (Elhanafy et al. 2008) or the applicability of the kinematic and diffusive wave equations are the main scope of several studies (Liggett & Woolhiser 1967, Ponce & Simons 1977, Ponce et al. 1978, Moussa & Bocquillon 1996b, Bajracharya & Barry 1997), the evaluation of modelling strategies is that of Horritt & Bates (2002), while parameter estimation is addressed, among others, by Koussis et al. (1978).

### 2.5.2 Erosion

Whereas common practices in fluid mechanics and hydraulics are rather to seek context-specific strategies in erosion modelling, two simplifying and unifying trends, if not paradigms, have developed in the field of hydrology. The first one is the transport capacity concept (Foster & Meyer 1972) in which the erosive strength of the flow decreases with increasing suspended sediment load, until a switch occurs from detachment- to transport-limited flows. The second one is the stream power concept (Bagnold 1956) that *slope times discharge* is the explicative quantity for erosion, with adaptations that mentioned unit stream power (*slope times velocity*, Yang 1974, Govers 1992) or fitted exponents to the slope and discharge terms (Julien & Simmons 1985). Many catchment-scale hydrology-erosion models (e.g. ANSWERS: Beasley et al. 1980, CREAMS: Knisel 1980, KINEROS: Smith et al. 1995, LISEM: De Roo et al. 1996, WEPP: Ascough et al. 1997, EUROSEM: Morgan et al. 1998, MAHLERAN: Wainwright et al. 2008, MHYDAS-Erosion: Gumiere et al. 2011) adopt the 1D Diffusive or Kinematic Wave Equations to route water fluxes, possibly through vegetated strips (Muñoz-Carpena et al. 1999), together with the simplest possible couplings between water and sediment fluxes (Aksoy & Kavvas 2005).

A known difficulty when embracing larger scales with simplified models is to describe the spatially-distributed sources and sinks of sediments (Jetten et al. 1999, 2003) with or without explicit descriptions of the permanent or temporary connectivity lines, for water and sediment movements (Prosser & Rustomji 2000, Croke & Mockler 2001, Pickup & Marks 2001, Bracken et al. 2013). What tends to force reduced complexity approaches in erosion models is the necessity to handle distinct detachment, transport and deposition processes (from the very shallow diffuse flows formed during runoff initiation to the regional-scale basin outlets) with only sparse data on flow structure and soil characteristics (cohesion, distribution of particle sizes, bed packing). Parsons & Abrahams (1992) have established how the agronomical, engineering and fluvial families of approaches have converged into similar modelling techniques, especially on the subject of erosion in overland flows (Prosser & Rustomji 2000). The ASV formalism also allows fitting bedload transport formulae against mean discharge values as a surrogate to the overcomplicated explicit descriptions of erosion figures in high-gradient streams with macro-roughness elements (Smart 1984, Aziz & Scott 1989, Weichert 2006, Chiari 2008). ASV-level couplings have also been applied to study the slope independence of stream velocity in eroding rills (Gimenez & Govers 2001) and the appearance of bed patterns in silt-laden rivers (van Maren 2007).

# 3 Determinants of modelling choices

This section aims at the construction of a signature for each case study, relating the "conceptual" choice of a model refinement (Navier-Stokes: NS, Reynolds-Averaged Navier-Stokes: RANS, Saint-Venant: SV or Approximations to Saint-Venant ASV) to the "contextual" descriptors, i.e. the spatiotemporal scales (section 3.1), spatiotemporal scales and flow typologies (section 3.2), spatiotemporal scales, flow typologies and dimensionless numbers (section 3.3). Figures 2, 3, 5, 6 and 7 in this section were drawn from the 158 studies listed in Appendix A.

## 3.1 Spatiotemporal scales

### 3.1.1 Influence of domain length (L) and time scale (T)

A cross-disciplinary analysis of the cited literature indicates a clear correlation between the (L, T) scales and the chosen model refinement (NS, RANS, SV or ASV). In this (L, T) plane, Fig. 2 quantifies the expected trend that sophisticated (NS, RANS) models are required to represent rapidly-varying small-scale phenomena (lower left) while simplified approaches (ASV) pertain to increased durations and spatial extensions (upper right). Typical scales of application may be identified for each model refinement: NS (10 cm<L<100 m, 10 s<T<1 hr), RANS (1 m<L<100 m, 10 s<T<1 hr), SV (10 m<L<20 km, 1 min<T<5 days) and ASV (10 m<L<1000 km, 30 min<T<1 yr). However, some studies consider larger spatial or temporal scales, for example Charru et al. (2004) for overland granular flows (RANS, L~20 cm, T~2 days) or Rathburn & Wohl (2003) for pool-riffle sequences (SV, L~70 m, T~30 days). Nevertheless, the existence of overlap regions suggests that the (L, T) spatiotemporal scales are not the only factor governing the choice of flow models.

The influence of flow typologies is discussed later in details but could the modelling choices be dictated by the scientific background of the modeller? A striking example is that of the SV models, responsible for the largest overlaps in Fig. 2. They may for example be used by physicists, as an upgraded alternative to the NS equations, in the field of environmental fluid mechanics (for limited scales). They may as well be convenient for soil scientists interested in high-resolution hydrology or for civil engineers who may need to cope with flow unsteadiness to handle erosion issues or to allow correct sizing of the man-made structures (for somewhat wider scales).

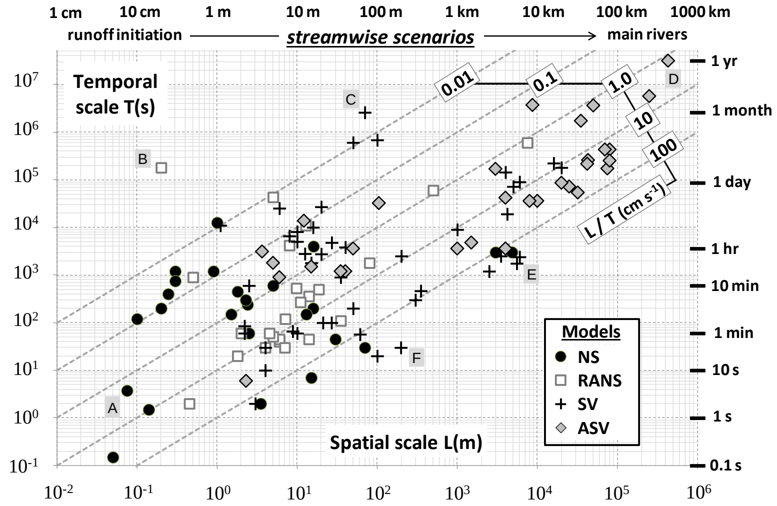


**Figure 2 – How increasing (L, T) spatiotemporal scales of the flow domain tend to be associated with decreasing complexity in the choice of flow models, sorted here into four levels of refinement: Navier-Stokes (NS), Reynolds-Averaged Navier-Stokes (RANS), Saint-Venant (SV) or Approximations to Saint-Venant (ASV). A transverse analysis involves forming L/T ratios, searching for clues to model selection according to these "system evolution velocities" or governed by flow typologies that would exhibit specific L/T ratios. This figure was assembled from information available in the studies cited in Appendix A, selecting six textbook cases (sketches A to F, Table 1) for illustration.**

Figure 2 bears another type of information than the trend to decreasing model refinement with increasing spatiotemporal scales. As the x-ordinate indicates the spatial scale L and the y-ordinate the time scale T, then the L/T ratio has dimensions of a velocity. However, this quantity should not be interpreted as a flow velocity. It rather indicates which of the temporal (long-term, low L/T ratio) or spatial (short-term, high L/T ratio) aspects are predominant in the study. Hence, the five dotted diagonals (L/T=$10^{-4}$, $10^{-3}$, $10^{-2}$, 0.1 and 1 m $s^{-1}$) establish the numerical link between the spatial and temporal scales of the cited experiments. They also show the dispersion with respect to the expected (say "natural") correlation between increasing L and T values. This dispersion contains a lot of information. Judging from the plotted literature, the lowest L/T ratios (e. g. $10^{-4}$ m $s^{-1}$) tend to indicate systems with low "evolution velocities", possibly associated with long-term changes or effects (high T values, low L values) obtained from repeated phenomena, multiple cycles and progressive modifications. By contrast, high L/T ratios (e.g. 1 m $s^{-1}$) rather refer to single-event situations, more associated with quick modifications of flow patterns or bed morphologies.

If rules of thumb in problem dimensioning were to be drawn from Fig. 2, geomorphological concerns (dune migration, basin sedimentation, long-term bed modifications) probably require stretching up the temporal scale so that low "system evolution velocities" would fall beneath L/T=$10^{-2}$ m $s^{-1}$ while event-based modelling (dam breaks, formative discharges, flash floods) should be able to handle high "system evolution velocities" near or beyond L/T=1 m $s^{-1}$. This "fixed-L, chosen-T" description of system evolution and characteristic time scales also refers to Fig. 1 in which the choice of T is somehow left at the modeller's discretion, as a degree of freedom: how different from $T_0$ should T be? These points are the subject of detailed investigations in the field of morphodynamics (Paola et al. 1992, Howard 1994, Van Heijst et al. 2001, Allen 2008, Paola et al. 2009). Indicators of "system evolution velocities" with units of a velocity but different definitions may for example be found in Sheets et al. (2002), who took the channel depth (H) divided by the average deposition rate to obtain a relevant, characteristic time scale (T). For the same purpose, Wang et al. (2011) took the characteristic bed roughness (ε) instead of channel depth. The objective is often to discriminate what Allen (2008) called the "reactive" (high L/T) and "buffer" (low L/T) systems. With or without erosion issues, a reasonable hypothesis here seems that the dispersion in L/T ratios arises from the variety of flow contexts, which may necessitate different modelling strategies. In other terms, it is deemed in this study that this secondary trend, associated with flow typologies, is also a determinant in the choice of the flow model.

To take a few examples and guide the reader through the arguments and the figures of this paper, Table 1 gathers the information available for the six textbook cases outlined by sketches A to F in Fig.2. The selected studies represent a wide variety of cases (drawing an approximate envelop of cases in the L-T plane of Fig.2) followed in the forthcoming stages of the analysis and associated figures in

Section 3.1.2 (determinants of modelling choices in the L-H plane, Fig.3), Section 3.2 (determinants sought in flow typology, Fig.6a and 7a) and Section 3.3 (determinants sought in the values of dimensionless numbers attached to the flow).

| Case | Context | Authors | Model refinement | Spatiotemporal scales | | | | | Flow typology‡ | Dimensionless numbers§ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | L (m) | T (s) | H (m) | L/T (m $s^{-1}$) | H/L† (-) | | T* | Re | Fr | S (%) | $\Lambda_z$ | θ |
| A | Film flow | Charpin & Myers (2005) | NS | 0.075 | 3.75 | 0.003 | 0.02 | 0.04 | O | 5 | 300 | 0.11 | 10 | 8.0 | - |
| B | Laminar dynamics | Charru et al. (2004) | RANS | 0.2 | 1.8 $10^5$ | 0.007 | 1.1 $10^{-6}$ | 0.035 | O | 6428 | 50 | 0.02 | <0.01 | 12.1 | 0.14 |
| C | Pool-riffles | Rathburn & Wohl (2003) | SV | 70 | 2.6 $10^6$ | 0.47 | 3.5 $10^{-5}$ | 6.7 $10^{-3}$ | B | 7.8 $10^4$ | 7.1 $10^5$ | 0.69 | 1.1 | 5108 | 34.1 |
| D | Amazon River | Trigg et al. (2009) | ASV | 4.3 $10^5$ | 3.15 $10^8$ | 10 | 1.4 $10^{-3}$ | 2.3 $10^{-5}$ | F | 58.5 | 8 $10^5$ | 0.05 | <0.01 | 6600 | - |
| E | Step-pools | Grant et al. (1990) | SV | 5530 | 1755 | 0.87 | 3.15 | 1.5 $10^{-4}$ | Hg | 1.0 | 2.7 $10^6$ | 1.03 | 4.5 | 1.25 | - |
| F | Step-pools | Chin (1999) | SV | 197.25 | 30 | 0.50 | 6.58 | 0.025 | Hg | 1.21 | 4.0 $10^6$ | 3.58 | 6.25 | 1.22 | - |

† See section 3.1.2 - H/L is the fineness ratio of the flow comparing flow depth (H) to the length of the flow domain (L)
‡ See Section 3.2 - O: Overland, Hg: High-gradient, B: Bedforms, F: Fluvial
§ See Section 3.3 - T*: dimensionless period, Re: Reynolds number, Fr: Froude number, S: slope, $\Lambda_z$ inundation ratio, θ Shields number

**Table 1 - Six textbook cases representing an approximate envelope of all the tested cases in the L-T plane of Fig.2, where L is the spatial scale (length of the flow domain) and T the temporal scale (duration of the process studied). Spatiotemporal scales are the determinants of modelling choices discussed in Section 3.1. The additional influence of flow typology and dimensionless numbers are discussed in Sections 3.2 and 3.3.**

### *3.1.2 Influence of domain length (L) and flow depth (H)*

The NS, RANS, SV and ASV equations are now positioned with respect to the spatial scale (L) and flow depth (H) of the reported experiments (Fig. 3), showing patterns and trends very similar to those of the (L, T) plane, though less pronounced . The global trend stays a decrease in refinement of the flow models from the smallest to the largest (L, H) values and typical scales of application may again be identified for each model refinement, NS (10 cm<L<100 m, 1 mm<H<30 cm), RANS (1 m<L<100 m, 5 cm<H<50 cm), SV (10 m<L<20 km, 1 cm<H<2 m) and ASV (10 m<L<1000 km, 10 cm<H<10 m). Some studies provide outliers for example Gejadze & Copeland (2006) for canal control purposes (NS, L~3 km, H~10 m) or Cassan et al. (2012) for flows in lined channels (RANS, L~50 cm, H~75 cm). In an overview, wider overlaps and more dispersion occur in the (L, H) than in the (L, T) plane, especially for low to medium scales: flow depth (H) seems less discriminating than the time scale (T) in the choice of a flow model.

The transverse analysis of H/L "fineness ratios" (dotted diagonals H/L=$10^{-1}$, $10^{-2}$, $10^{-3}$, $10^{-4}$ and $10^{-5}$) provides additional information, or rather a complementary reading grid on the information already plotted. First, only the NS and RANS models allow 2D (x, z) flow descriptions, which explains why these models have many of the largest H/L ratios (which, in most cases, stay within the H<<L shallow water hypothesis). Second, low H/L ratios provide justifications to discard 2D (x, z) descriptions at the benefit of 1D (x) descriptions within but also without the NS and RANS formalisms, so that the second diagonal of Fig. 3 (roughly from the upper right to the lower left) also shows a decrease in model refinement, towards SV and ASV points.

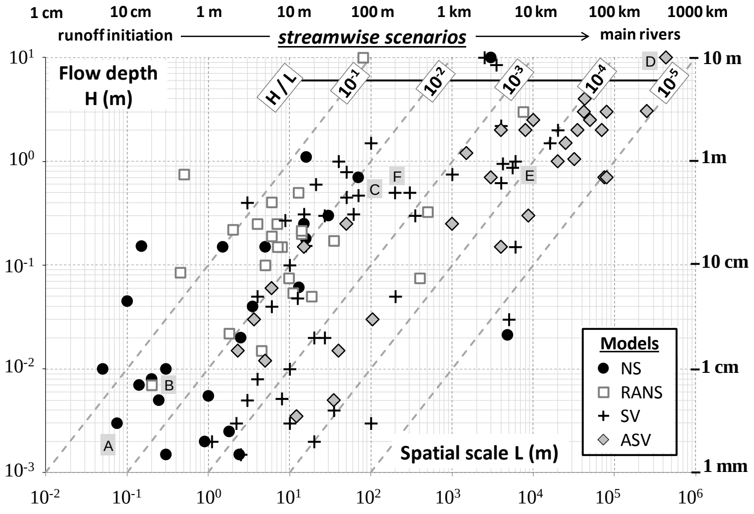


**Figure 3 – How increasing (L, H) spatiotemporal scales of the flow domain tend to be associated with decreasing complexity in the choice of flow models, sorted here into four levels of refinement: Navier-Stokes (NS), Reynolds-Averaged Navier-Stokes (RANS), Saint-Venant (SV) and Approximations to Saint-Venant (ASV). A transverse analysis involves forming H/L ratios, searching for clues to model selection according to the "fineness" of the flow or governed by flow typologies that would exhibit specific H/L ratios. This figure was assembled from information available in the studies cited in Appendix A, selecting six textbook cases (sketches A to F, Table 1) for illustration.**

### 3.1.3 Influence of domain length (L), time scale (T) and flow depth (H)

The links between model refinements (NS, RANS, SV or ASV) and spatiotemporal scales (L, T, H) were shown in the (L, T) and (L, H) planes (Fig. 2 and 3). There was first the expected correlation between increasing scales and decreasing model refinements. Then the transverse analyses involved re-examining the same dataset from the values of the L/T and H/L ratios, also seeking the determinants of modelling choices in the "system evolution velocity" (L/T) and "fineness" of the flow (H/L).

- The values of the L/T ratios indicate that modelling choices owe much to the long-term (low L/T) or short-term (high L/T) objectives associated with the target variables (velocity, discharge, particle transport, bed modifications) thus influencing the choice of T values. However, this choice is not totally free: it is likely constrained by flow characteristics and typologies.
- The values of the H/L ratios also indicate that flow typology (here, only its "fineness" is explicit) may be a mattering determinant for the choice of a modelling strategy. This idea is explored in far more details hereafter. The next section outlines the influence of friction, flow retardation and energy dissipation processes on flow typology. It advocates thus the definition of flow typologies from quantities related to the different types and/or magnitudes of flow retardation processes, provided these quantities are easily accessible (e.g. bed geometry, water depth, bed slope, size of the roughness elements).

## 3.2 Flow typology

### 3.2.1 From friction laws and bed topography to flow characteristics

Early insights on fluid friction and the definition of shear stress proportional to local velocity gradients came together with the action-reaction law (Newton 1687): friction exerted on the flow was of equal magnitude as the erosive drag, originally termed "critical tractive force" (Du Buat 1779) and held responsible for particle detachment. The friction laws mostly resorted to in present-day modelling do not often involve adaptations or  generalisations of their famous empirical predecessors in civil engineering (Chézy 1775, Weisbach 1845, Darcy 1857, Manning 1871) even if practitioners and modellers are now confronted to far less controlled bed topographies and flow conditions, thus to a wider variety of flow typologies. The theoretical  derivation (or justification) of contextually relevant friction laws seems therefore crucial, for water flow modelling at the microscopic (Richardson 1973, Jansons 1988, Priezjev & Troian 2006) or macroscopic scales (Smith et al. 2007, Powell 2014), and even more for erosion issues. In the literature, the modelling choices to account for friction phenomena are most often correlated with the refinement of the flow models used (NS, RANS, SV, ASV) but also constrained by bed topographies and flow typologies in numerous cases.

Several studies at the NS level of refinement advocate the use of the "partial slip" (Navier 1827) condition or parented formulations in which the near-bed slip velocity is either proportional to the shear stress (Jäger & Mikelic 2001, Basson & Gerard-Varet 2008) or depends on it in a non-linear way (Achdou et al. 1998, Jäger & Mikelic 2003). Other works plead for "no-slip" conditions (Panton 1984, Casado & Diaz 2003, Myers 2003, Bucur et al. 2008, 2010) or suggest the separation of flow domains within or outside bed asperities, with a complete slip condition (non-zero tangential velocity) at the interface (Gerard-Varet & Masmoudi 2010). A wider consensus exists at the RANS level, calculating bottom friction as the local grain-scale values of the "Reynolds stresses" (Kline et al. 1967, Nezu & Nekagawa 1993, Keshavarzy & Ball 1997), which has proven especially relevant for flows in small streams over large asperities (Lawless & Robert 2001, Nikora et al. 2001, Pokrajac et al. 2007, Schmeeckle et al. 2007). However, he who can do more, can do less, and it is still possible to use the simplest empirical friction coefficients (Chézy, Manning) within sophisticated flow descriptions (NS: Lane et al. 1994, RANS: Métivier & Meunier 2003). In the literature, the SV level of refinement is a tilting point in complexity, that allows fundamental research, deriving ad hoc shear stress formulae from the local fluid-solid interactions (Gerbeau & Perthame 2001, Roche 2006, Devauchelle et al. 2007, Marche 2007) or applied research, adjusting parameter values in existing expressions, for specific contexts (e.g. boulder streams: Bathurst 1985, 2006, step-pool sequences: Zimmermann &

Church 2001, irrigation channels: Hauke 2002, gravel-bed channels: Ferro 2003). This trend holds for most studies at the ASV level of refinement, though theoretical justifications of Manning's empirical formula were recently derived (Gioia & Bombardelli 2002) and a recent mathematical study of the diffusive wave equation (Alonso et al. 2008) introduces generalized friction laws for flows over non-negligible topographic obstacles. The event-based variability of the friction coefficient in ASV models has been investigated by Gaur & Mathur (2002).

If not decided from the level of refinement of the flow model, the friction coefficient (*f*) is chosen in accordance with flow typology and bed topography, the former often described by the Reynolds number (*Re*), the latter by the inundation ratio ($\Lambda_z$=H/ε where ε is the size of bed asperities, to which flow depth H is compared). Such arguments were already present in the works of Keulegan (1938) and Moody (1944) on flow retardation in open-channel and pipe flows, relating values of the friction coefficient to the relative roughness (ε/H=1/$\Lambda_z$) of the flow, across several flow regimes (laminar, transitional, turbulent) but only for small relative roughness (high inundation ratios). The existence of implicit relations between *f*, Re and $\Lambda_z$ has somehow triggered the search for contextual alternatives to the sole *f*-Re relation for turbulent flows. Progressively lower inundation ratios were investigated (Smith et al. 2007) until the real cases of emergent obstacles received attention (Bayazit 1976, Abrahams & Parsons 1994, Bathurst 2006, Meile 2007, Mügler et al. 2010) including for non-submerged vegetation (Prosser et al. 1995, Nepf 1999, Järvelä 2005, Nikora et al. 2008). For site-specific friction laws, the default *f*-Re relation is sometimes complemented by *f*-Fr trends (Grant 1997, Gimenez et al. 2004, Tatard et al. 2008) or *f*-$\Lambda_z$ relations (Peyras et al. 1992, Chin 1999, Chartrand & Whiting 2000, Church & Zimmermann 2007) in steep bed morphologies, where Fr is the Froude number (Froude 1868).

Knowledge gained on flow retardation processes lead to the identification of key dimensionless groups, to be included in any comprehensive analysis, formed from the "obvious", available elements of bed geometry previously mentioned (Julien & Simons 1985, Lawrence 2000, Ferro 2003, Yager et al. 2007). In numerous practical cases though, explicit bed geometries cannot be handled by the flow models. A crucial surrogate becomes then to include as many geometrical effects as possible in the chosen friction laws, for example these obtained from composite roughness experiments (Schlichting 1936, Colebrook & White 1937, Einstein & Banks 1950). A crucial advance was due to Smith & McLean (1977) who attributed distinct retardation effects to bed particles, particle aggregates and bedforms, corresponding to “grain spill”, “obstructions” and “long-wave form resistance” in the subsequent literature. From then on, friction forces exerted by multiple roughness elements or scales have often been described as additive-by-default, in shallow overland flows (Rauws 1980, Abrahams et al. 1986), gravel-bed streams (Bathurst 1985, Lawless & Robert 2001, Ferro 2003), natural step-pool formations (Chin & Wohl 2005, Canovaro & Solari 2007, Church & Zimmermann 2007) and man-made spillways or weirs (Peyras et al. 1992, Chinnarasri & Wongwise 2006).

### *3.2.2 From flow characteristics to flow typologies*

Several authors have put forward the existence of a scale-independent link between bed geometry, flow retardation and flow structure, through the existence of three distinct flow regimes, from geometrical arguments: "isolated roughness", "wake interference" and "skimming" flow (Morris 1955, 1959, Leopold et al. 1960, Fig. 4a, c and e). These flow descriptions were later applied in very different contexts (Abrahams & Parsons 1994, Chanson 1994a, Papanicolaou et al. 2001, Zimmermann & Church 2001), which suggests that analogies in energy dissipation and flow retardation may exist across scales, from similar geometries and flow characteristics. This makes the description somewhat generic, possibly used to constitute a set of flow typologies.

In Fig. 4a, the isolated roughness flow is laminar or weakly turbulent and the shade (streamline diversion) of an obstacle does not reach the next. This setting ensures maximum energy dissipation, which also holds for stepped cascades of natural or man-made nature in Fig. 4b: "nappe flows" loose strength through energy-consuming fully-developed hydraulic jumps, isolated behind the major obstacles (Peyras et al. 1992, Chanson 1994b, Wu & Rajaratnam 1996, 1998). In Fig. 4c the wake-interference flow is transitional or turbulent. The drag reduction and partial sheltering between obstacles depend on their spatial distribution and arrangements, as in Fig. 4d that shows "partial nappe flow" in relatively flat step-pool formations, with incomplete hydraulic jumps between obstacles of irregular sizes and spacing (Wu & Rajaratnam 1996, 1998, Chanson 2001). In Fig. 4e, the turbulent skimming flow exhibits a coherent stream cushioned by the recirculating fluid trapped between obstacles and responsible for friction losses. Similar characteristics appear in Fig. 4f, for submerged cascades or large discharges on stepped spillways. Air entrapment begins where the boundary layer reaches the free surface and flow aeration triggers subscale energy dissipation (Rajaratnam 1990, Chanson 1994b).

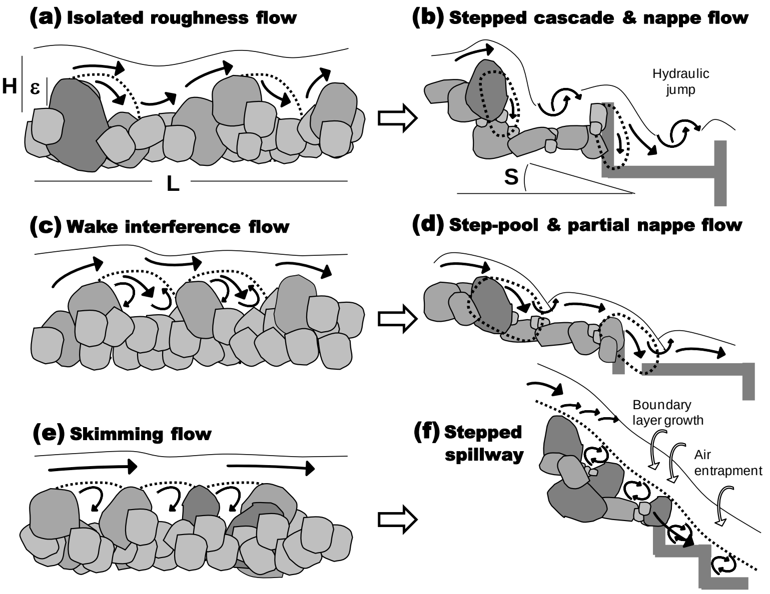


**Figure 4 – Analogies in flow characteristics, retardation processes and energy dissipation structures for very different flow typologies: streams (a, c, e) and high-gradient natural or man-made stepped flows (b, d, f). The combined values of flow depth (H), slope (S) and inundation ratio ($\Lambda_z$=H/ε, where ε is the roughness size) appear as strong geometrical controls over flow characteristics and typologies.**

At this point, our set of flow typologies should be obtained from the geometrical arguments available in Fig. 4 (water depth H, bed slope S, inundation ratio $\Lambda_z$=H/ε). The simplest way to proceed is to work in the (S, H) plane, then to add a criterion on $\Lambda_z$ if the values of S and H are not discriminating enough. The first two flow typologies (Overland flow, noted O, and High-gradient flow, noted Hg) may be identified by a single criterion on H only ($H<H_{LIM}$, Emmett 1970, Wainwright et al. 2008) or on S only ($S>S_{LIM}$, Grant et al. 1990, Rosgen 1994, Montgomery & Buffington 1997). At least two flow typologies remained to be distinguished, Fluvial flows (F) and flows over significant bedforms (e.g. rough plane bed, dune-ripples or pool riffles, as suggested by Montgomery & Buffington 1997), referred to as Bedforms (B) in the following. Though Fluvial flows are expected to have the highest flow depths, an additional criterion on $\Lambda_z$ may be used to make the difference between these last two typologies. Figure 5 positions the selected (O, Hg, B, F) flow typologies in the (S, H) plane.

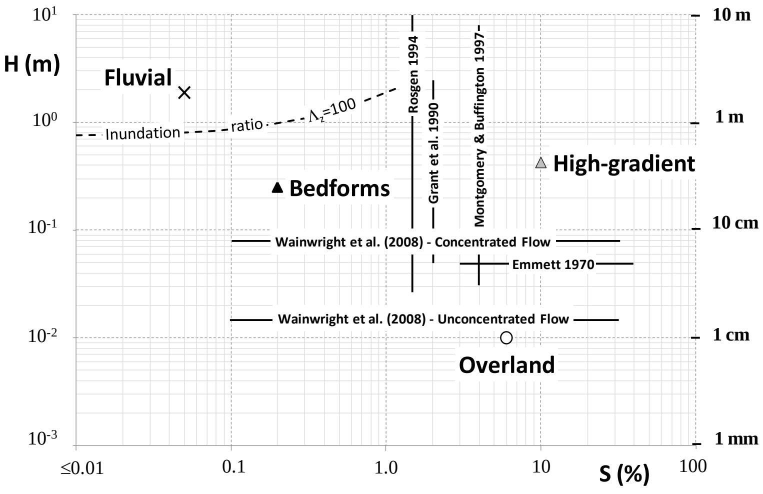


**Figure 5 – Median position of the studies belonging to the "Overland", "High-gradient", "Bedforms" and "Fluvial" flow typologies, plotted on the (S: slope, H: water depth) plane, also tracing an approximate additional criterion on the inundation ratio ($\Lambda_z$=H/ε, where ε is the size of the bed asperities) to separate**

**the Fluvial and Bedforms types of flow. This figure was assembled from information available in the studies cited in Appendix A.**

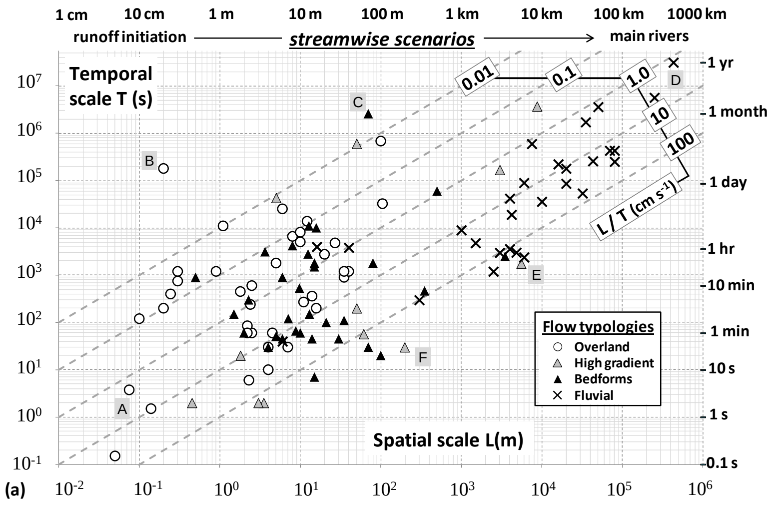
Moreover, there is a strong link between Fig. 4 and 5, which tends to ensure the genericity (if not uniqueness) of the selected set of typologies. The Overland typology corresponds to Fig. 4a or c, the Bedforms typology likely appears in Fig. 4c, the Fluvial typology in Fig. 4 and the High-gradient typology in Fig. 4b, d or f. In coherence with Fig. 5, an increase in bed slope changes the Bedforms and Fluvial typologies into the High-gradient typology, while an increase in both water depth and bed slope is needed to do the same from the Overland typology.

### *3.2.3 Influence of flow typologies on modelling choices*

Figures 6 and 7 provide a comprehensive picture of the most used associations between models (NS, RANS, SV or ASV), scales (L, T, H) and flow typologies (O, Hg, B or F) just added to the analysis. These figures seem to indicate preferential [NS, O], [RANS, B] and [SV, Hg] associations, in addition to the obvious [ASV, F] pair. The (L, H) plot of Fig. 6 seems more discriminating than the (L, T) plot of Fig. 7 though identical trends appear.

The [NS, O] association arises from the fact that several Overland studies involve very shallow laminar flows and low sediment transport rates, best handled by adapted formulations of the NS equations (nearly at the SV level), made suitable for low "system evolution velocities" ($L/T \approx 0.01$ m $s^{-1}$, Fig. 6). At somewhat larger spatial scales, the widely-used and multipurpose SV model has rather low median $L/T \approx 0.02$ m $s^{-1}$ values, mainly because many of its applications concern laminar flow modelling and granular transport, as an alternative to the NS system or in formulations at complexity levels intermediate between the NS and SV descriptions. These are clues that the [SV, O] association may also be of special interest, despite the closest median positions of the NS and O points in the (L, T) and (L, H) plots.

The RANS model (median L/T≈0.07 m $s^{-1}$) and the ASV models (median L/T≈0.1 m $s^{-1}$) tend to involve higher "system evolution velocities". The former typically targets the description of numerous short-term, high-frequency events (quadrant analysis for fluctuations in near-bed velocity, particle pick-up by turbulent bursts). The latter is often associated with Fluvial flows: low H/L ratios with high enough H and $\Lambda_z$ values with weak friction, often resulting in very turbulent, high-velocity flow. Moreover, studies handling erosion issues within the ASV formalism often hypothesize particle transport to occur as suspended load only, equating particle and flow velocities, thus typically not extending the time scale of the study to address the long-term, low velocity bedload transport involved in morphodynamics, for example.



**Mis en forme :** Retrait : Première ligne : 0.5 cm

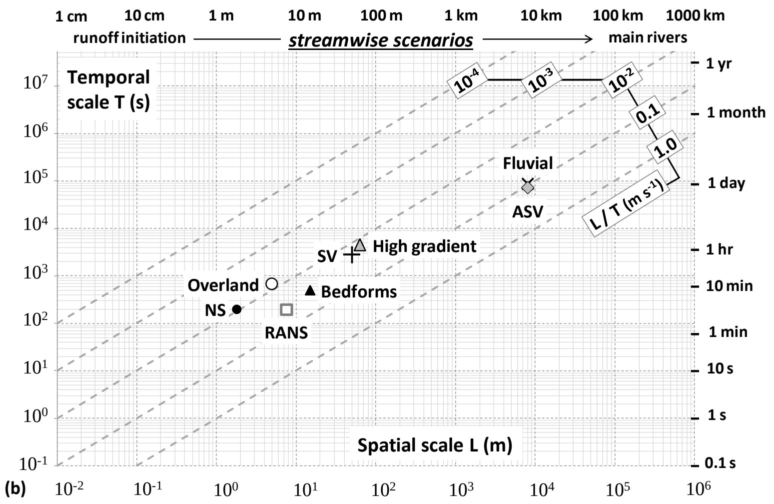
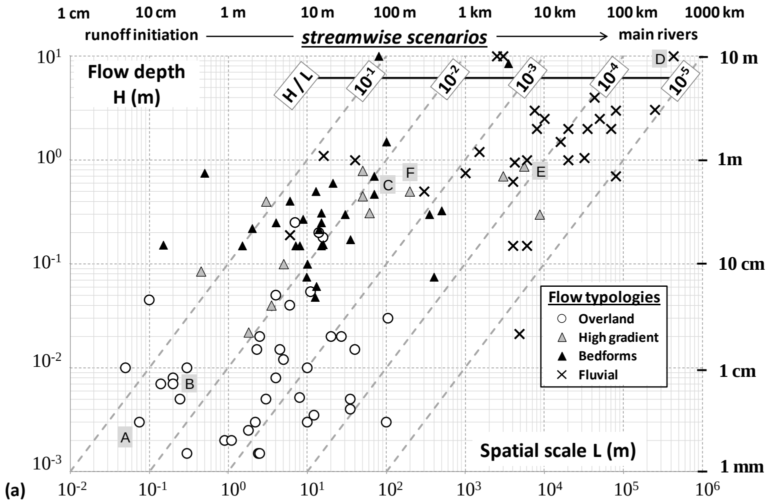


**Figure 6 – Position of the flow typologies in the (L, T) plane for the studies listed in Appendix A, selecting six textbook cases (sketches A to F, Table 1) for illustration (a). Median positions for the choice of free-surface flow models (Navier-Stokes: NS, Reynolds-Averaged Navier-Stokes: RANS, Saint-Venant: SV or Approximations to Saint-Venant: ASV) and the study of flow typologies (Overland, High-gradient, Bedforms or Fluvial) across scales in the (L, T) plane (b). A transverse analysis involves forming L/T ratios, searching for clues to model selection according to these "system evolution velocities" or governed by flow typologies that would exhibit specific L/T ratios.**



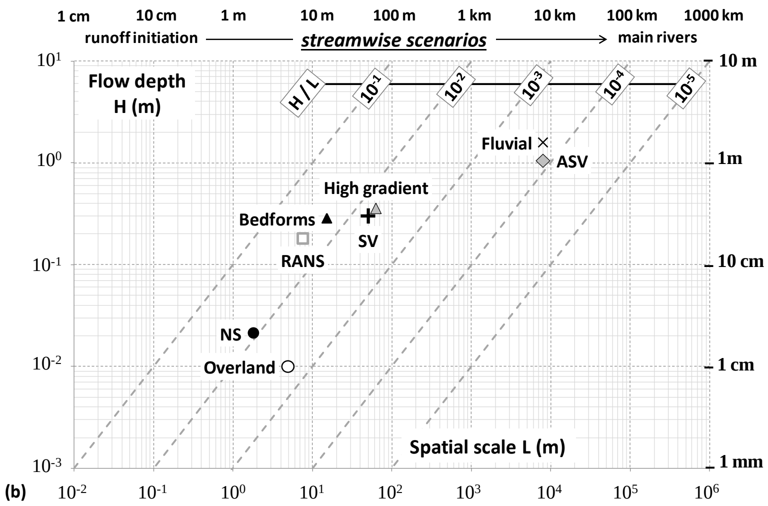


**Figure 7 – Position of the flow typologies in the (L, H) plane for the studies listed in Appendix A, selecting six textbook cases (sketches A to F, Table 1) for illustration (a). Median positions for the choice of free-surface flow models (Navier-Stokes: NS, Reynolds-Averaged Navier-Stokes: RANS, Saint-Venant: SV or Approximations to Saint-Venant: ASV) and the study of flow typologies (Overland, High-gradient, Bedforms or Fluvial) across scales in the (L, H) plane (b). A transverse analysis involves forming H/L ratios, searching for clues to model selection according to these "finenesses" of the flow domain or governed by flow typologies that would exhibit specific H/L ratios.**

Several principles of organization between flow typologies may be inferred from reference studies (Grant et al. 1990, Montgomery & Buffington 1997, Church 2002) that discuss their succession in space (along longitudinal profiles) but also in time (which flow typologies are "experienced" by the flowing water during its course and which are the associated time scales). Plausible "streamwise scenarios" may therefore be assembled (Fig. 8), routing flow aggregations across increasing spatiotemporal scales and through several flow typologies, from the narrow-scale upland flows (runoff initiation) to the regional scales of the main rivers.

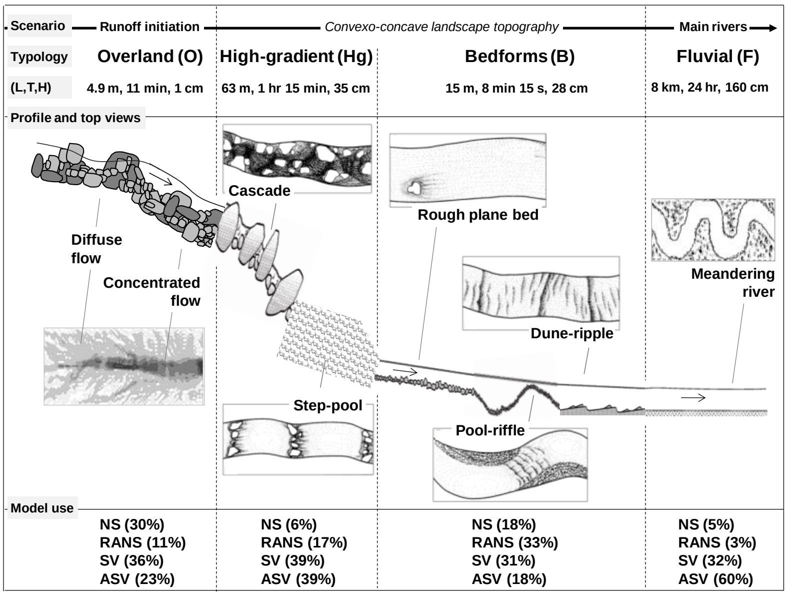


**Figure 8 – Streamwise scenario for a convexo-concave landscape topography, from runoff initiation to the main rivers, across flow typologies (Overland O, High-gradient Hg, Bedforms B or Fluvial F) and spatiotemporal scales (L, T, H). The indicated L, T and H values are the median values for the spatial scale, time scale and water depth, respectively, from the literature cited in Appendix A (Fig. 6 and 7). All sketches and drawings for the High-gradient and Bedforms typologies were taken from Montgomery & Buffington (1997). The top view for Overland flow is from Tatard et al. (2008) and that of a meandering river from Rosgen (1994). The "model use" panel indicates the model refinement most used (Navier-Stokes NS, Reynolds-Averaged Navier-Stokes RANS, Saint-Venant SV or Approximations to Saint-Venant ASV) to describe a given flow typology in the literature.**

## *3.3 Dimensionless numbers*

### *3.3.1 Contextual dimensionless numbers*

An angle of attack for the establishment of modelling strategies is provided by dimensional analysis, to delineate the domains of validity of the selected flow models (NS, RANS, SV or ASV), across their multiple spatiotemporal scales of application but in a powerful scale-independent analysis. Justifications for the use of dimensionless numbers may be sought in the developments of similitude laws (Fourier 1822, Rayleigh 1877, Bertrand 1878, Vaschy 1892, Riabouchinsky 1911), later extended to dimensional analysis, providing guidance for the sizing of experimental facilities used in reduced-scale modelling as well as more general arguments for the choice of adequate sets of dimensionless quantities (Buckingham's 1914 $\pi$-theorem, Bridgman 1922, Langhaar 1951, Bridgman 1963, Barenblatt 1987). Throughout history, the establishment of dimensionless numbers has led to the recognition of contextually dominant terms in the flow equations, rendering them prone to dedicated simplifications, provided these would not be used outside their conditions of validity, following successive hypotheses made during their derivation.

From a wide overview of free-surface flow and erosion studies, a few dimensionless numbers stood out and will be used in the procedure presented in the following. Some have already been mentioned (Reynolds number Re, Froude number Fr) and some others have even been used to define flow typologies (bed slope S, inundation ratio $\Lambda_z$). As all dimensionless numbers aim to describe flow typology, the introduction of two more dimensionless numbers may be seen as an attempt to re-examine the influence of flow typologies on modelling choices, from a different, more complete perspective (especially if the dimensionless numbers not used in the definition of flow typologies prove discriminating for the modelling choices).

- The dimensionless period $T^*=T/T_0$ handles temporal aspects by comparing the chosen time scale (T) to the natural time scale ($T_0$) of the system, the latter obtained from the spatial scale of the system and the average flow velocity as $T_0$=L/U (Fig. 1). This dimensionless group or equivalent formulations are used to model wave celerity in flood propagation issues (Ponce & Simons 1977, Moussa & Bocquillon 1996a, Julien 2010) or to quantify the long characteristic times (T*>>1) of basin-scale sedimentation. In the latter, particle transport (and significant bed modifications) typically involve lower velocities (and larger time scales) than these of water flow (Paola et al. 1992, Howard 1994, Van Heijst et al. 2001) and the chosen T value witnesses this discrepancy.

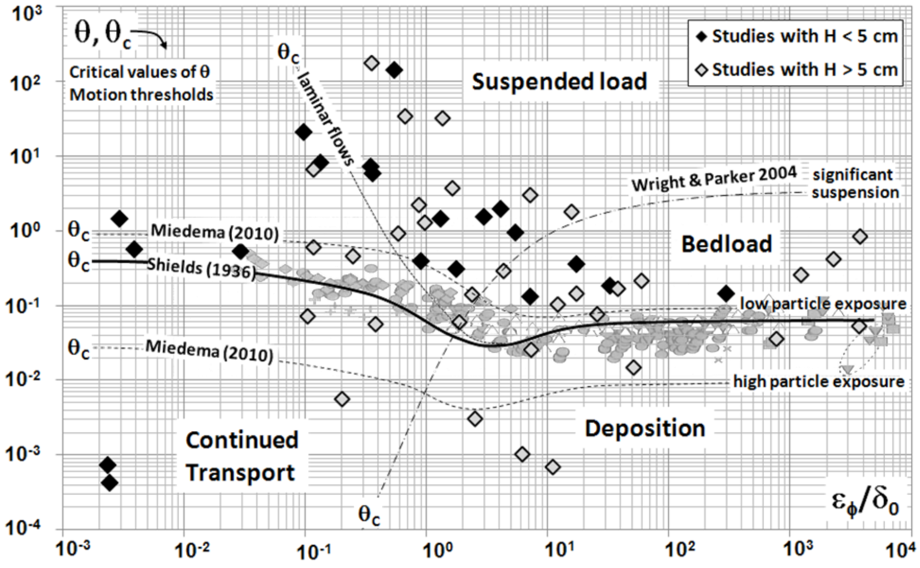
- The Reynolds number Re=UH/υ compares flow inertia (velocity U times depth H) with the adverse action of (kinematic) viscosity (υ [L $T^{-2}$]). In natural setting, over very rough boundaries, fully turbulent flows are often reported for Re>2000, while the onset of turbulence within transitional regimes occurs at Re~500. Laminar overland flows, especially thin film flows, may have Re values as low as Re<100.

- The Froude number Fr=U/$(gH)^{0.5}$ denotes the influence of gravity (g) on fluid motion. Supercritical Fr>1 values indicate torrential flows, accelerated by pressure effects, in which waves propagate only downstream, also compatible with the appearance of localised energy dissipation patterns (white waters, hydraulic jumps). Subcritical Fr<1 values indicate tranquil flows with downstream controls.

- Topographical effects on flow phenomenology are almost always explicitly accounted for through the average bed slope S, typically ranging from nearly zero (S<0.01%) for large rivers to extremely high values (S ≈ 100%) for gabion weirs, chutes or very steep cascades.

- Topography also appears through the inundation ratio $\Lambda_z$=H/ε which allows a direct, model-independent analysis of friction phenomena (Lawrence 1997, 2000, Ferguson 2007, Smith et al. 2007) possibly dealing with large-size obstacles and form-induced stresses (Kramer & Papanicolaou 2005, Manes et al. 2007, Cooper et al. 2013). The encountered values of $\Lambda_z$ are very high for rivers flowing on smooth, cohesive, fine-grained beds ($\Lambda_z$>100) and very low for all types of flows between emergent obstacles ($\Lambda_z$<1).

- The dimensionless Shields number $\theta = \tau_0 / g\varepsilon_p(\rho_p - \rho)$ compares the drag force exerted on bed particles to their immersed weight, where $\varepsilon_p$ and $\rho_p$ account for the size and density of erodible particles.. The ratio between the current $\theta$ and the critical $\theta_c$ values indicates local flow conditions of deposition ($\theta < \theta_c$), incipient motion ($\theta \approx \theta_c$), transportation as bedload ($\theta > \theta_c$) or into suspension ($\theta >> \theta_c$) (Shields 1936). This number seems appropriate for most erosion issues because it has been widely applied and debated in the literature (Coleman 1967, Ikeda 1982, Wiberg & Smith 1987, Zanke 2003, Lamb et al. 2008) and also because of its numerous possible adaptations (Neill 1968~~, Parker et al. 2003~~, Ouriémi et al. 2007, Miedema 2010) to various flow typologies and non-uniform or poorly-known bed conditions. An impressive review on the use of the Shields number to determine incipient motion conditions, over eight decades of experimental studies, may be found in Buffington & Montgomery (1997). Finally, Fig.9 provides a generalized Shields diagram that includes motion threshold criteria under the effects of high or low particle exposure (Miedema 2010) or for laminar flows, also indicating the conditions of significant suspension (Wright & Parker 2004).



**Mis en forme :** Couleur de police : Automatique

**Figure 9 - Generalized dimensionless Shields diagram that summarizes the conditions and regimes of sediment transport or deposition, from the relative values of the Shields parameter ($\theta$) and incipient motion criterion ($\theta_c$). The X-axis bears the values of the ratio of particle size ($\varepsilon_\phi$) on the depth of the laminar sublayer ($\delta_0$). The diamonds refer to the studies cited in Appendix A that deal with erosion issues: black diamonds for studies in which flow depth is H<5 cm, grey diamonds otherwise. Data in the background show the critical $\theta_c$ values reported in the wide Buffington & Montgomery (1993) review of incipient motion conditions for varied flow regimes, particle forms and exposures.**

### *3.3.2 Influence of the dimensionless numbers*

As the purpose here is to re-examine the influence of flow typologies from the angle of the dimensionless numbers, the chosen representation (Fig. 10~~9~~) discards the (L, T, H) spatiotemporal scales. It first recalls the preferential associations between models and flow typologies (see the "model use" panel of Fig. 8) by tracing connecting dotted lines between flow typologies and the models most used to handle them, in the legend of Fig. 10~~9~~. It then examines whether these associations still hold, for each of the six dimensionless numbers, by plotting and comparing the median values of T*, Re, Fr, S, $\Lambda_z$ and $\theta$ for model uses (NS, RANS, SV or ASV) and flow typologies (O, Hg, B, F). The dotted ellipses are "confirmations" (e.g. no additional information may likely be obtained from Re, Fr and $\theta$). Conversely, the presence of "non-associated" points ($P_1$ for T*, $P_2$ and $P_3$ for S, $P_4$ for $\Lambda_z$) signals something new: an influence not yet accounted for.

For example, the isolated $P_1$ point indicates the expected ASV-F association does not appear on the T* values, as the ASV applications exhibit higher median T* values than the F typologies. The suggested interpretation is that large (L, T, H) scales and Fluvial flows likely trigger the use of the ASV model, though the necessity to handle large dimensionless periods makes the typological argument less conclusive. The $P_2$ and $P_3$ points indicate the break of the NS-O and ASV-F associations when examined from the angle of the bed slopes. This reinforces the use of bed slopes in the search for determinants of modelling choices, either in the definition of flow typologies in the (S, H) plane or as such. The $P_4$ point indicates the break of the NS-O association when considering the values of the inundation ratio, with the same conclusion as above.

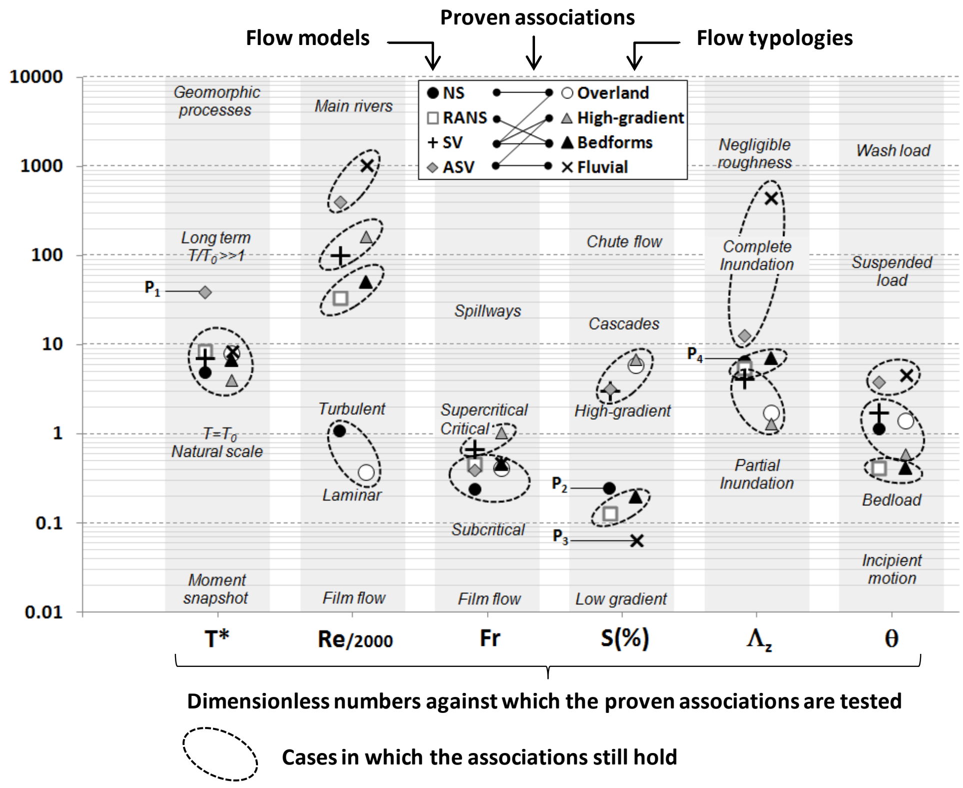


**Figure 109 - Comparative overview of the median values of the six selected dimensionless numbers (dimensionless period $T^*=T/T_0$, ratio of the chosen time scale on the "natural" time scale of the flow, Reynolds number Re, Froude number Fr, slope S, inundation ratio $\Lambda_z$ and Shields parameter θ) obtained for the use of systems of equations (NS, RANS, SV and ASV) and the description of flow typologies (O, Hg, B and F) in the cited literature. The expected associations are indicated by dotted connecting lines in the legend box. The confirmed associations are indicated by dotted ellipses. Broken associations (isolated points $P_1$ to $P_4$) are discussed in the text. The typical and extreme ranges of the mentioned dimensionless numbers have been added for indication. This figure was assembled from information available in the studies cited in Appendix A.**

# 4 Conclusion

## 4.1 Outcomes of this review

In a free opinion on the use of models in hydrology, De Marsily (1994) elegantly argued that the modelling of observable phenomena should obey "*serious working constraints, well-known from classical tragedy: unity of place, unity of time, unity of action*". This review paper investigates how known spatial scales, temporal scales and flow typologies constrain the choice of a modelling strategy. A normative procedure was built to facilitate the search for determinants of the modelling choices in the cited literature.

- Each free surface flow model was placed in one of the NS, RANS, SV or ASV categories, whose decreasing levels of refinement account for "Navier-Stokes", "Reynolds-Averaged Navier-Stokes", "Saint-Venant" or "Approximations to Saint-Venant" types of approaches.

- The explored (L, T, H) spatiotemporal scales cover multiple orders of magnitude in the streamwise direction (5 cm< L<1000 km), the time duration (0.1 s<T<1 yr) and flow depth (1 mm<H<10 m).

- This study also encompasses a wide variety of free-surface flows, reduced to four typologies from arguments on bed geometry, friction, flow retardation and energy dissipation processes. These typologies are Overland flow (O: diffuse or concentrated), High-gradient flow (Hg: cascades, step-pools), flows over significant Bedforms (B: rough plane beds, dune ripples, pool riffles) and Fluvial flows (F: rivers, canals). Overland flows have the shallowest depths, High-gradient flows the highest bed slopes, Fluvial flows have high flow depths and negligible bed roughness while Bedforms flows may have any flow depth, over pronounced, non-negligible bedforms.

- In addition to the spatiotemporal scales and flow typologies, the determinants of modelling choices are also sought in a series of six popular dimensionless numbers: the dimensionless period (T*), Reynolds and Froude numbers (Re, Fr), the bed slope (S), the inundation ratio ($\Lambda_z$=H/ε where ε is the size of bed asperities) and the Shields number (θ) that compares drag forces to particle weight.

In summary, each case-study may be defined by its signature, comprised of the chosen model (NS, RANS, SV or ASV), the given spatiotemporal scales (L, T, H), flow typology (O, H, B or F) and dimensionless numbers (T*, Re, Fr, S, $\Lambda_z$, $\theta$). Though non-unique, this signature is a generic and normative classification of studies interested in free-surface flow modelling, with or without erosion issues.

- The present review first illustrated the expected dominant trend of decreasing model refinement with increasing (L, T, H) spatiotemporal scales. It appeared then that model uses could also be sorted by their L/T and H/L ratios, though less clearly, which nevertheless provided indications that the spatiotemporal scales were not the only determinant of modelling choices. This result suggested that flow typologies (reduced here to the L/T "system evolution velocity" and H/L "fineness of the flow") were also influential factors.

- A more exhaustive set of flow typologies was then derived from simple geometrical arguments, combining criteria on S, H and $\Lambda_z$, represented in the (S, H) plane. This allowed quantifying the median scales associated with studies interested in the Overland (O), Bedforms (B), High-gradient (Hg) and Fluvial (F) typologies, sorted here by increasing spatiotemporal scales. Then came the identification of preferential associations between flow models, scales and typologies: [NS, O] or [SV, O], [RANS, B] or [SV, B], [SV, Hg] or [ASV, Hg] and [ASV, F] for increasing spatiotemporal scales.

- The final step was to re-examine the previous associations from the values of the dimensionless numbers, thought here as more detailed, scale-independent descriptors of flow typologies. Several associations were confirmed by the median values of the associated dimensionless numbers but the T* (dimensionless period), S (bed slope) and $\Lambda_z$ (inundation ratio) introduced additional information., i.e. correcting trends.

All arguments prevailing in the identification and sorting of flow models, scales, typologies and dimensionless numbers may easily be debated and adapted, within the hydrology-erosion community or for other research purposes. For example, multiple flow models, scales, typologies and dimensionless numbers also intervene in the fields of pesticide fate modelling and groundwater contamination issues, so the same procedure could be applied. Finally, this procedure offers the possibility to enrich the database of signatures if each modeller records his (or her) conceptual choices (flow models) in the proposed reading grid, together with the contextual elements (scales, typologies, dimensionless numbers) handled, for present and past studies. This would first help forming a comprehensive view of modelling choices, thus seeking guidance from "what has been done in similar cases", which however does not provide any critical analysis. Complementary investigations could certainly address the question of "what should be done", this time deciding the "model" part of the signatures from recommendations based on the scales, typologies and dimensionless numbers, as well as from additional elements, typically the modelling objectives (Figure 11).

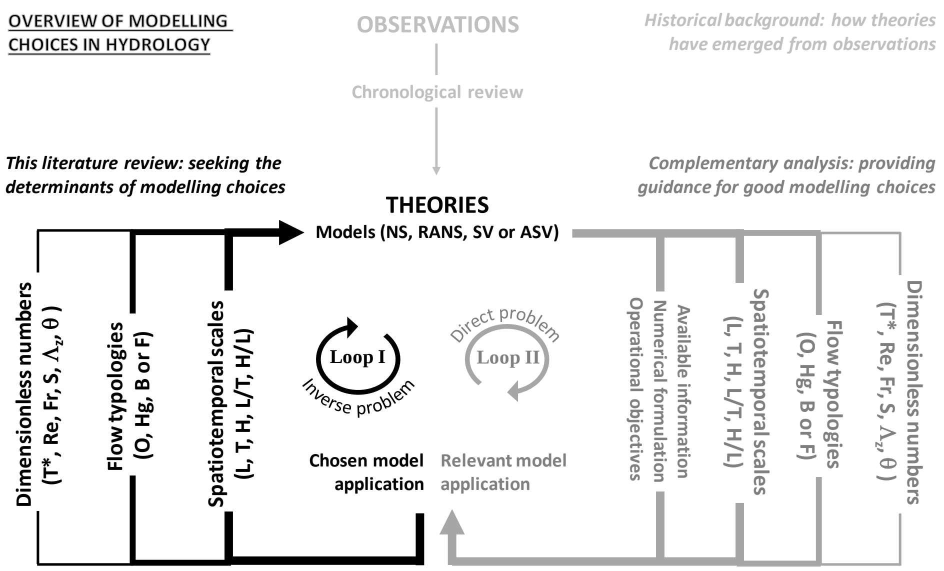


**Figure 11 – This figure provides a simplified overview of the available modelling choices in hydrology, in three distinct colours associated with specific research purposes or disciplines, showing the position of the present review relative to the others. The pale grey section aims at understanding how the available flow models have emerged from observations and early formulations of the flow equations, focusing on their conditions of validity i.e. the successive hypotheses made during their derivation. The black section recalls the procedure followed in this review paper (Loop I, "inverse problem"). Literature sources are processed through a procedure that analyses how the spatiotemporal**

**scales (spatial scale L, time scale T, flow depth H, L/T and H/L ratios), then flow typology (Overland O, High-gradient Hg, Bedforms B or Fluvial F) and dimensionless numbers (dimensionless period T*, Reynolds number Re, Froude number Fr, bed slope S, inundation ratio $\Lambda_z$, Shields parameter θ) determine the choice of a flow model (Navier-Stokes NS, Reynolds-Averaged Navier-Stokes RANS, Saint-Venant SV or approximations ASV). Suggested in medium grey on the right are the scope and principles of future research challenges that would address the "*what should be done?*" (Loop II, "direct problem") question in echo to the current "*what has been done?*"concern (Loop I).**

## *4.2 Research challenges in hydrology and philosophy of modelling*

This review has sought the determinants of modelling choices in hydrology (Figure 11, Loop I) from the basis provided by literature sources, without any intention to provide recommendations. However, for most practical applications, the starting point is the definition of a scope and the endpoint is the evaluation of the objective function to evaluate the success or the failure of the chosen modelling strategy. A question thus arises on how to guide the modeller in the choice of an adequate model, in function of given, approximately known spatiotemporal scales, flow typology and dimensionless numbers (Figure 11, Loop II). According to the principle of parsimony, modellers should seek the simplest modelling strategy capable of (i) a realistic representation of the physical processes, (ii) matching the performances of more complex models and (iii) providing the right answers for the right reasons.

- (i) Throughout the last decades, an important change of the scope of free-surface flow modelling applications has taken place, with subsequent changes in the objective functions resorted to. The development of hydrological and hydraulic sciences has been directly linked to the progresses in understanding processes, in theoretical model development (e.g. computational facilities: numerical techniques, data assimilation, thorough model exploration, inverse calculus) and in data acquisition (new devices, remote sensing, LiDAR). "*It may seem strange to end a review of modelling with an observation that future progress is very strongly linked to the acquisition of new data and to new experimental work but that, in our opinion, is the state of the science*" (Hornberger & Boyer 1995).

- (ii) However, there remains an important need for research on classical free-surface flow (hydrological or hydraulic) modelling for engineering applications in predicting floods, designing water supply infrastructures and for water resources management, from the headwater catchment to the regional scale. More recently, free-surface flow modelling has become an indispensable tool for many interdisciplinary projects, such as predicting pollution and/or erosion incidents, the impact of anthropogenic and climate change on environmental variables such as water, soil, biology, ecology, or socio-economy and ecosystemic services. The direct consequence is a significant increase of the complexity of the objective function, from simple mono-site (e.g. one-point), mono-variable (e.g. the water depth) and mono-criterion (e.g. the error on peakflow) to complex multi-site (e.g. large number of points within a catchment), multi-variable (e.g. water depth, hydrograph, water table, concentrations, ecological indicators, economic impact) and multi-criteria (e.g. errors on peakflow, volume, RMSE) objective functions.

- (iii) There is often a mismatch between model types, site data and objective functions. First, models were developed independently from the specificities of the study site and available data, prior to the definition of any objective function. In using free-surface flow models, the context of their original purpose and development is often lost, so that they may be applied to situations beyond their validity or capabilities. Second, site data are often collected independently of the objectives of the study. Third, the objective function must be specific to the application but also meet standard practices in evaluating model performance, in order to compare modelling results between sites and to communicate the results to other scientists or stakeholders. The known danger is to use flow and erosion equations outside their domains of validity (*i.e.*, breaking the assumptions made during their derivation) then to rely on the calibration of model parameters as for technical compensations of theoretical flaws, at the risk of losing the physical sense of model parameters, creating equifinality and obtaining the "*right results for the wrong reason*" (Klemeš 1986). Choosing the right model for the right reason is crucial but the identification of the optimal data-model couple to reach a predefined objective is not straightforward. We need a framework to seek the optimum balance between the model, data and the objective function as a solution for a hydrological or hydraulic problem, on the basis of  the principle of parsimony. The latter follows a famous quote often attributed to Einstein, that "*everything should be made as simple as possible, but not simpler"* which somehow originates in the philosophy of William of Ockham (1317) *(Numquam ponenda est pluralitas sine necessitate [Plurality must never be posited without necessity])* or may even be traced back to Aristotle's (~350 BCE) *Analytica Posteriora* that already advocated demonstrations relying on the fewest possible number of conjectures, i.e. the dominant determinisms.

Finally, analytical procedures for free-surface flows and erosion issues necessitates a comprehensive analysis of the interplay between models (assumptions, accuracy, validity), data requirements and all contextual information available, encompassed in the "signature" of any given application: model refinement, spatiotemporal scales, flow typology and scale-independent description by dimensionless numbers. This review helps the modeller positioning his (or her) case study with respect to the modelling practices most encountered in the literature, without providing any recommendation. A complementary step and future research challenge is to decipher relevant modelling strategies from the available theoretical and practical material, resorting to the same objects, the previously defined signatures. Its purpose clearly is to address the "*which model, for which scales and objectives?*" question. A complete analytical framework, comprised of both loops, would provide references and guidelines for modelling strategies. Its normative structure in classifying theoretical knowledge (the mathematics world, equations and models) and contextual descriptions (real-life physical processes, scales and typologies) hopefully makes it also relevant for other Earth Sciences.

# Appendix A. References used in the Figures.

Abrahams & Parsons (1994), Afzalimehr & Anctil (2000), Afzalimehr et al. (2007), Akan & Yen (1981), Alonso et al. (2002), Audusse et al. (2008), Aziz & Scott (1989), Bajracharya & Barry (1997), Bates & De Roo (2000), Bathurst (2006), Belaud & Paquier (2001), Beltaos et al. (2012), Berger & Stockstill (1995), Blandford & Meadows (1990), Booker et al. (2001), Bounvilay (2003), Burguete et al. (2008), Camacho & Lees (1999), Canovaro & Solari (2007), Cao et al. (2004), Cassan & Belaud (2012), Cassan et al. (2012), Chahinian et al. (2005), Charlier (2007), Charlier et al. (2009), Charpin & Myers (2005), Charru et al. (2004), Chartrand & Whiting (2000), Chen & Wu (2000), Chiari (2008), Chin (1999), Chinnarasri and Wongwise (2006), Choi & Molinas (1993), Church & Zimmermann (2007), Davies et al. (1997), Devauchelle et al. (2007), Dunkerley (2003), Dunkerley (2004), Einstein (1950), Elhanafy et al. (2008), Emmett (1970), Engelund & Fredsoe (1976), Fan & Li (2006), Feng & Michaelides (2002), Fovet et al. (2013), Gao & Abrahams (2004), Garcia & Parker (1993), Gaur & Mathur (2003), Gejadze & Copeland (2006), Gerbeau & Perthame (2001), Ghavasieh et al. (2001), Gimenez & Govers (2001), Gimenez et al. (2004), Gomez-Delgado et al. (2011), Govers (1992), Grant et al. (1990), Guinot & Cappelaere (2009), Hallema & Moussa (2013), Hauke (2002), Hayami (1951), Henine et al. (2014), Hessel (2006), Hessel et al. (2003), Horritt & Bates (2002), Hromadka & DeVries (1988), Jain & Singh (2005), Järvelä (2005), Keshavarzy & Ball (1997), Keskin & Agiralioglu (1997), Keulegan (1938), Koussis (1978), Lajeunesse et al. (2010), Lamarre & Roy (2008), Lamb et al. (2008), Lane et al. (1994), Lawless & Robert (2001), Lawrence (2000), Leopold et al. (1960), Liang et al. (1996), Liu et al. (2003), Liu et al. (2007), Lobkosvsky et al. (2008), Lyn (1992), Malverti et al. (2008), Mangeney et al. (2007), McDonald et al. (1995b), Meile (2007), Métivier & Meunier (2003), Meyer-Peter & Müller (1948), Mizanur & Chaudhry (1995), Mohapatra & Ballamudi (1996), Morgan et al. (1998), Morin et al. (2009), Moussa (1996), Moussa & Bocquillon (1996a), Moussa & Bocquillon (1996b), Moussa & Bocquillon (2009), Moussa & Chahinian (2009), Moussa et al. (2002), Moussa et al. (2007), Mügler et al. (2010), Munier et al. (2008), Nepf (1999), Nikora et al. (2001), Nikora et al. (2008), Nino et al. (2003), Nord & Esteves (2010), Paiva et al. (2013), Parsons et al. (1997), Perkins & Koussis (1996), Perumal & Price (2013), Peyras et al. (1992), Pokrajac et al. (2007), Polyakov & Nearing (2003), Ponce et al. (1978), Ponce et al. (1996), Prahl et al. (2007), Prosser et al. (1994), Rathburn & Wohl (2003), Rauws (1980), Reddy et al. (2007a), Reddy et al. (2007b), Rodellar et al. (1993), Roux & Dartus (2006), Rutschmann & Hager (1996), Saleh et al. (2013), Sau et al. (2010), Savat (1980), Schindler & Robert (2004), Schmeeckle & Nelson (2003), Schmeeckle et al. (2007), Sear (1996), Sen & Garg (2012), Shields (1936), Simpson & Castelltort (2006), Sivakumaran & Yevyevich (1987), Sivapalan et al. (1997), Smart (1984), Smith & McLean (1977), Stevenson et al. (2002), Tatard et al. (2008), Tiemeyer & al. (2007), Todini & Bossi (1986), Trigg et al. (2009), van Maren (2007), Vieux et al. (2004), Wang & Chen (2003), Wang et al. (2006), Wang et al. (2014), Weichert (2006), Williams (1970), Wainwright et al. (2008), Wu & Lee (2001), Yager et al. (2007), Zhou (1995), Zimmermann & Church (2001), Zoppou & O'Neill (1982).

# Acknowledgements

The authors would like to thank Gilles Belaud (SupAgro Montpellier), Claude Bocquillon (University of Montpellier II) and Pierre-Olivier Malaterre (IRSTEA Montpellier) for fruitful discussions. We are also grateful to the two anonymous peer reviewers for their recommendations and to HESS for financial support.

# References

Abbott, M. B. (1979). Computational Hydraulics. Pitman, London, 324pp.

Abrahams, A. D. and Parsons, A. J. (1994). Hydraulics of interrill overland flow on stone-covered desert surfaces, Catena, 23, pp.111-140.

Achdou, Y, Pironneau, O. and Valentin, F. (1998). Effective boundary conditions for laminar flows over periodic rough boundaries, Journal of Computational Physics, 147, pp.187-218.

Afzalimehr, H. and Anctil, F. (1999). Velocity distribution and shear velocity behavior of decelerating flows over a gravel bed, Canadian Journal of Civil Engineering, 26 (4), pp.468-475.

Afzalimehr, H., Dey, S. and Rasoulianfar, P. (2007). Influence of decelerating flow on incipient motion of a gravel-bed stream, Sadhana-Academy Proceedings in Engineering Sciences, 32 (5), pp.545-559.

Akan, A. O. and Yen, B. C. (1981). Diffusion-wave flood routing in channel networks. Journal of the Hydraulic Division, ASCE, vol 107, N°HY6, pp.719-732.

Aksoy, H. and Kavvas, M. L. (2005) A review of hillslope and watershed scale erosion and sediment transport models, Catena, 64 (2-3), pp.247-271.

Alavian, V., Jirka, G. H., Denton, R. A., Johnson, M. A., Stefan, H. G. (1992). Density currents entering lakes and reservoirs, Journal of Hydraulic Engineering, 118 (11), pp.1464-1489.

Allen, P. A. (2008). Time scales of tectonic landscapes and their sediment routing systems, Geological Society of London, Special Publications, 296, pp.7-28.

Alonso, C. V., Bennett, S. J. and Stein, O.R. (2002). Predicting head cut erosion and migration in concentrated flows typical of upland areas, Water Resources Research, 38 (12), 1303.

Alonso, R., Santillana, M. and Dawson, C. (2008). On the diffusive wave approximation of the shallow water equations, European Journal of Applied Mathematics, 19 (5), pp.575-606.

Ascough II, J. C., Baffaut, C., Nearing, M. A. and Liu, B.Y. (1997). The WEPP watershed model: I. Hydrology and erosion, Transactions of the ASAE, 40(4), pp.921–933.

Audusse, E., Bristeau, M. O. and Decoene, A. (2008). Numerical simulations of 3D surface flows by a multilayer Saint-Venant model, International Journal for Numerical Methods in Fluids, 56 (3), pp.331-350.

Aziz, N. M. and Scott, D. E. (1989). Experiments on sediment transport in shallow flows in high gradient channels, Hydrological Sciences Journal, 34, pp.465–478.

Bagnold, R. A. (1954). Experiments on the gravity-free dispersion of large solid spheres in a Newtonian fluid under shear, Proceedings of the Royal Society of London-Series A, 225 (964), pp.49-63.

Bagnold, R. A. (1956). The flow of cohesionless grains in fluids, Philosophical Transactions of the Royal Society of London, 249 (964), pp.235-297.

Bagnold, R. A. (1966). An approach to the sediment transport problem from general physics, US Geological Survey Professional Paper 442-I, Washington D.C., US Government Printing Office, 42 pp.

Bajracharya, K. and Barry, D. A. (1997). Accuracy criteria for linearised diffusion wave flood routing, Journal of Hydrology, 195 (1-4), pp.200-217.

Barenblatt, G. I. (1987) Dimensional Analysis, New York: Gordon and Breach Science Publishers, 135 pp.

Basson, A. and Gerard-Varet, D. (2008). Wall laws for fluid flows at a boundary with random roughness, Communications on Pure and Applied Mathematics, 61 (7), pp.941-987.

Bates, P. D. and De Roo, A. P. J. (2000). A simple raster-based model for flood inundation simulation, Journal of Hydrology, 236, pp.54-77.

Bates, P.D., Horritt, M.S. and Fextrell, T.J. (2010). A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation model. Journal of Hydrology, 387, 33-45.

Bathurst, J. C. (1985). Flow resistance estimation in mountain rivers, Journal of Hydraulic Engineering – ASCE, 111 (4), pp.625-643.

Bathurst, J. C. (2006). At-a-site variation and minimum flow resistance for mountain rivers, Journal of Hydrology, 269 (1-2), pp.11-26.

Bayazit, M. (1976). Free surface flow in a channel of large relative roughness, Journal of Hydraulic Research, 14 (2), pp.115-126.

Beasley, D.B., Huggins, L.F. and Monke, E.J. (1980). ANSWERS: a model for watershed planning. Transactions of the ASAE, pp.938-944.

Belaud, G. and Paquier, A. (2001). Sediment diversion through irrigation outlets, Journal of Irrigation and Drainage Engineering, 127 (1), pp.35-38.

Beltaos, S., Tang, P. and Rowsell, R. (2012). Ice jam modelling and field data collection for flood forecasting in the Saint John River, Canada. Hydrological Processes, 26, pp.2535- 2545.

Bennett, J. P. (1974). Concepts of mathematical modelling of sediment yield, Water Resources Research, 10, pp.485-492.

Bennett, S. J., Alonso, C. V, Prasad, S. N. and Römkens, M. J. M. (2000). Experiments on headcut growth and migration in concentrated flows typical of upland areas, Water Resources Research, 36 (7), pp.1911-1922.

Berger, R. C. and Stockstill, R. L. (1995). Finite-element model for high-velocity channels. J Hydraulic Engineering, 121, 10, pp.710-715.

Bertrand, J. (1878). Sur l'homogénéité dans les formules de physique, Comptes Rendus de l’Académie des Sciences, 86 (15), pp.916–920.

Best, J.L. (1992), On the entrainment of sediment and initiation of bed defects: insights from recent developments within turbulent boundary layer research, Sedimentology, 39, pp.797-811.

Beven K. J. (2000). Rainfall-runoff modelling, the primer, John Wiley & Sons, Chichester, UK 360 pp

Blandford, G. E. and Meadows, M. E. (1990). Finite element simulation of nonlinear kinematic surface runoff. Journal of Hydrology, 119, pp.335-356.

Blöschl, G. and Sivapalan, M. (1995). Scale issues in hydrological modeling: a review, Hydrological Processes, 9, pp.251-290.

Boardman, J. (2006). Soil erosion science: Reflections on the limitation of current approaches, Catena, 68 (2-3), pp.73-86.

Booker, D. J., Sear, D. A. and Payne, A. J. (2001). Modelling three-dimensional flow structures and patterns of boundary shear stress in a natural pool-riffle sequence, Earth Surface Processes and Landforms, 26, pp.553-576.

Bouchut, F., Mangeney-Castelnau, A., Perthame, B., Vilotte, J.-P. (2003). A new model of Saint-Venant and Savage-Hutter type for gravity driven shallow water flows, Comptes-Rendus de l'Académie des Sciences de Paris, 336, pp.531-536.

Bouchut, F. and Westdickenberg, M. (2004). Gravity-driven shallow water models for arbitrary topography, Communications in Mathematical Sciences, 2, pp.359-389.

Bounvilay, B. (2003). Transport velocities of bedload particles in rough open channels flows, PhD Thesis, Department of Civil Engineering, Colorado State University, USA, 2003.

Boussinesq, J. (1877). Essai sur la théorie des eaux courantes. Mémoires à l'Académie des Sciences. T23-24, pp.1-680.

Bracken, L. J., Wainwright, J., Ali, G. A., Tetzlaff, D., Smith, M. W., Reaney, S. M. and Roy, A. G. (2013). Concepts of hydrological connectivity: research approaches, pathways and future agendas, Earth Science Reviews, 119, pp.17-34.

Bridgman, P.W. (1922). Dimensional Analysis, Yale University Press, New Haven.

Bridgman, P.W. (1963). Dimensional Analysis, Yale Paperbound, New Haven, 113 pp.

Buckingham, E. (1914). On physically similar systems; illustrations of the use of dimensional equations, Physical Review, 4, pp.345-376.

Bucur, D., Feireisl, E. and Necasova, S. (2010). Boundary behavior of viscous fluids: influence of wall roughness and friction-driven boundary conditions, Archive for Rational Mechanics Analysis, 197 (1), pp.117-138.

Bucur, D., Feireisl, E., Necasova, S. and Wolf, J. (2008). On the asymptotic limit of the Navier-Stokes system on domains with rough boundaries, Journal of Differential Equations, 244 (11), pp.2890-2908.

Buffington, J. M. and Montgomery, D. R. (1997). A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. Water Resources Research, 33, pp.1993-2029.

Burguete, J., Garcia-Navarro, P. and Murillo, J. (2008). Friction-term Discretization and limitation to preserve stability and conservation in the 1D shallow-water model: application to unsteady irrigation and river flow, International Journal for Numerical Methods in Fluids, 58, pp.403-425.

Camacho, L. A. and Lees, M. J. (1999). Multilinear discrete lag-cascade model for channel routing, Journal of Hydrology, 226, pp.30-47.

Campisano, A., Creaco, E. and Modica, C. (2004). Experimental and numerical analysis of the scouring effects of flushing waves on sediment deposits, Journal of Hydrology, 299 (3-4), pp.324-334.

Canovaro, F. and Solari, L. (2007). Dissipative analogies between a schematic macro-roughness arrangement and step-pool morphology, Earth Surface Processes and Landforms, 32 (11), pp.1628-1640.

Cao, Z., Pender, G., Wallis, S. and Carling, P. (2004). Computational dam-break hydraulics over erodible sediment bed, Journal of Hydraulic Engineering-ASCE, 130 (7), pp.689-703.

Carlier M. (1980). Hydraulique générale et appliquée. Eyrolles, Paris, 565 pp.

Carollo, F.G., V. Ferro, and D. Termini (2005), Analyzing turbulence intensity in gravel bed channels, Journal of Hydraulic Engineering, 131 (12), pp.1050-1061.

Casado-Diaz, J., Fernandez-Cara, E. and Simon, J. (2003). Why viscous fluids adhere to rugose walls: a mathematical explanation, Journal of Differential Equations, 189 (2), pp.526-537.

Cassan, L. and Belaud, G. (2012). Experimental and numerical investigation of flow under sluice gates, Journal of Hydraulic Engineering, 138, pp.367-373.

Cassan, L., Belaud, G., Baume, J. and Dejean, C. (2012) Seasonal Variation of Velocity Fields in Lined Channels: Impact on Flow Measurement. World Environmental and Water Resources Congress 20-22 May 2012: pp.2188-2197.

Chahinian, N., Moussa, R., Andrieux, P. and Voltz, M. (2005). Comparison of infiltration models to simulate flood events at the field scale, Journal of Hydrology, 306, pp.191-214.

Charlier, J.-B. (2007). Fonctionnement et modélisation hydrologique d'un petit bassin versant cultivé en milieu volcanique tropical. Thèse de Doctorat, Université de Montpellier 2, Montpellier, France, 246 pp.

Charlier, J.-B., Cattan, P., Voltz, M. and Moussa, R. (2009). Transport of a nematicide in surface and ground waters in a tropical volcanic catchment, Journal of Environmental Quality, 38, pp.1031-1041.

Charpin, J. P. F. and Myers, T. G. (2005). Modelling thin film flow with erosion and deposition, Advances in Water Resources, 28, pp.761-722.

Charru, F.  (2006). Selection of the ripple length on a granular bed sheared by a liquid flow, Physics of Fluids, 18, 121508.

Charru, F., Mouilleron-Arnould, H. and Eiff, O. (2004). Erosion and deposition of particles on a bed sheared by a viscous flow, Journal of Fluid Mechanics, 519, pp.59-80.

Chartrand, S. M. and Whiting, P. J. (2000). Alluvial architecture in headwater streams with special emphasis on step-pool topography, Earth Surface Processes and Landforms, 25, pp.583-600.

Chen, C. L. (1992). Momentum and energy coefficients based on power-law velocity profile. Journal of Hydraulic Engineering, ASCE, 118 (11), pp.1571-1584.

Chen, R. C. and Wu, J. L. (2000). The flow characteristics between two interactive spheres, Chemical Engineering Science, 55, pp.1143-1158.

Chézy, A. de (1775). Mémoire sur la vitesse de l'eau conduite dans une rigole donnée, Fonds Ancien de l'Ecole Nationale des Ponts et Chaussées – No.847. Reprinted in: Annales des Ponts et Chaussées, 60, 1921.

Chiari, M. (2008). Numerical modelling of bedload transport in torrents and mountain streams, Phd Thesis, University of natural resources and applied life sciences, Vienna, Austria, 212 pp.

Chin, A. (1999). The morphologic structure of step-pools in mountain streams, Geomorphology, 27, pp.191-204.

Chin, A. and Wohl, E. (2005). Toward a theory for step pools in stream channels, Progress in Physical Geography, 29 (3), pp.275-296.

Chinnarasri, C. and Wongwise, S. (2006). Flow patterns and energy dissipation over various stepped chutes, Journal of Irrigation and Drainage Engineering – ASCE, 132, pp.70-76.

Choi, G. W. and Molinas, A. (1993). Simultaneous solution algorithm for channel network modelling. Water Resources Research, 29 (2), pp.321-328.

Chow, V. T. (1959). Open-Channel Hydraulics. McGraw Hill, New York, 680 pp.

Church, M. (2002). Geomorphic thresholds in riverine landscapes, Freshwater Biology, 47, pp.541-557.

Church, M. and Zimmermann, A. (2007). Form and stability of step-pool channels: research progress, Water Resources Research, 43 (3), W03415, doi:10.1029/2006WR005037~~.~~

Colebrook, C. F. and White, C. M. (1937). Experiments with fluid friction in roughened pipes, Proceedings of the Royal Society of London – Series A: Mathematical and Physical Sciences, 161 (906), pp.367-381.

Coleman, N. L. (1967). A theoretical and experimental study of drag and lift forces acting on a sphere resting on a hypothetical streambed, in Proceedings of 12th IAHR Congress, vol. 3, pp. 185–192, Int. Assoc. of Hydraul. Eng. and Res., Madrid.

Cooper, J. R., Aberle, J., Koll, K. and Tait, S. J. (2013). Influence of relative submergence on spatial variance and form-induced stress of gravel-bed flows, Water Resources Research, 49, pp.5765-5777.

Croke, J. and Mockler, S. (2001). Gully initiation and road-to-stream linkage in a forested catchment, south-eastern Australia, Earth-Surface Processes and Landforms, 26, pp.205-217.

Cunge, J. A. (1969). On the subject of a flood propagation computation method (Muskingum method), Journal of Hydraulic Research, 7 (2), pp.205-230.

Cunge, J., Holly, F. M. and Verwey, A. (1980). Practical aspects of computational river hydraulics. Pitman Advanced Publishing Program, London, 420 pp.

Daluz Vieira, J.H. (1983). Conditions governing the use of approximations for the Saint-Venant equations for shallow water flow, Journal of Hydrology, 60, pp.43-58.

Darcy, H. (1857). Recherches expérimentales relatives au mouvement de l'eau dans les tuyaux, Mallet-Bachelier, Paris. 268 pages and atlas (in French).

Davies, A. G., Ribberink, J. S., Temperville, A. and Zyserman, J. A. (1997). Comparisons between sediment transport models and observations made in wave and current flows above plane beds, Coastal Engineering, 31, pp. 163-198.

de Marsily, G. (1986). Quantitative hydrogeology, Academic Press, Inc., Orlando, FL, USA, 464 pp.

de Marsily, G. (1994). On the use of models in hydrology (free opinion), Revue des Sciences de l'Eau, 7, pp.219-234.

de Roo, A. P. J., Wesseling, C. G. and Ritsema, C. J. (1996). LISEM: a single event physically-based hydrologic and soil erosion model for drainage basins. I: Theory, input and output, Hydrological Processes, 10, pp.1107–1117.

Devauchelle, O., Josserand, C., Lagrée, P.-Y. and Zaleski, S. (2007). Morphodynamic modelling of erodible laminar channels, Physical Review E, 76, 056318, doi: 10.1103/PhysRevE.76.056318~~.~~

Devauchelle, O., Malverti, L., Lajeunesse, E., Josserand, C., Lagrée, P.-Y. and Métivier, F. (2010). Rhomboid beach pattern : a laboratory investigation, Journal of Geophysical Research, 115, F02017, doi: 10.1029/2009JF001471~~.~~

Dey, S. and Papanicolaou, A. (2008). Sediment threshold under stream flow: a state-of-the-art review, KSCE Journal of Civil Engineering, 12 (1), pp.45-60.

Dittrich, A., and K. Koll (1997). Velocity field and resistance of flow over rough surfaces with large and small relative roughness, International Journal of Sediment Research, 12 (3), pp.21-33.

Drake, T.G., R.L. Shreve, W.E. Dietrich, P.J. Whiting, and L.B. Leopold (1988). Bedload transport of fine gravel observed by motion picture photography, Journal of Fluid Mechanics, 192, pp.193-217.

Du Boys, D. (1879). Le Rhône et les rivières à lit affouillables. Annales des Ponts et Chaussées, Série 5, 18, pp.141-195.

Du Buat, P. (1779). Principes d'hydraulique et de pyrodynamique vérifiés par un grand nombre d'expériences faites par ordre du gouvernement, Firmin Didot Ed., Paris

Dunkerley, D. (2003). Determining friction coefficients for interrill flows: the significance of flow filaments and backwater effects, Earth Surface Processes and Landforms, 28 (5), pp.475-491.

**Mis en forme :** Français (France)

Dunkerley, D. (2004). Flow threads in surface run-off: implications for the assessment of flow properties and friction coefficients in soil erosion and hydraulics investigations, Earth Surface Processes and Landforms, 29 (8), pp.1011-1026.

Einstein, H. A. (1950). The bed-load function for sediment transportation in open channel flows, US Department of Agriculture, Soil Conservation Service, Technical Bulletin No. 1026, 74 pp.

Einstein, H. A. and Banks, R. B. (1950). Fluid resistance of composite roughness, Transactions of the American Geophysical Union, 31 (4), pp.603-610.

Elhanafy, H., Copeland, G. J. M. and Gejadze, I. Y. (2008). Estimation of predictive uncertainties in flood wave propagation in a river channel using adjoint sensitivity analysis, International Journal for Numerical Methods in Fluids, 56 (8), pp.1201-1207.

Emmett, W. W. (1970). The hydraulics of overland flow on hillslopes. United States Geological Survey, Professional Paper 662-A, US Government Printing Office: Washington, DC.

Engelund, F. and Fredsoe, J. (1976). Sediment transport model for straight alluvial channels, Nordic Hydrology, 7 (5), pp.293-306.

Exner, F. M. (1925). Über die Wechselwirkung zwischen Wasser und Geschiebe in Flüssen, Sitzungsberichte der kaiserlichen Akademie der Wissenchaften Wien, Abteilung IIa, 134, pp.165-205.

Fan, P. and Li, J. C. (2006). Diffusive wave solutions for open channel flows with uniform and concentrated lateral inflow, Advances in Water Resources, 29, pp.1000-1019.

Feng, Z. G. and Michaelides, E. E. (2002). Interparticle forces and lift on a particle attached to a solid boundary in suspension flow, Physics of Fluids, 14 (1), pp.49-60.

Ferguson, R.l. (2007). Flow resistance equations for gravel- and boulder-bed streams. Water Resources Research, 43, W05427, doi: 10.1029/2006WR005422.

Fernandez-Luque, R., and van Beek, R.(1976). Erosion and Transport of Bed-Load Sediment, Journal of Hydraulic Research, 14(2), pp.127-144.

Ferrick, M. G. (1985). Analysis of wave types, Water Resources Research, 21, pp.209-212.

Ferro, V. (2003). Flow resistance in gravel-bed channels with large-scale roughness, Earth Surface Processes and Landforms, 28 (12), pp.1325-1339.

Fourier, J. B. (1822) Théorie analytique de la chaleur, Paris.

Fovet, O., Litrico, X., Belaud, G. and Genthon, O. (2013). Adaptive control of algae detachment in regulated canal networks, Journal of Hydroinformatics, 15 (2), pp.321-334.

French, R. H. (1985). Open-channel hydraulics, New York, McGraw-Hill, 705 pp.

Froude, W. (1868). Observations and suggestions on the subject of determining by experiment the resistance of ships, Correspondence with the Admiralty, Chelston Cross, December 1868. Reprinted in "The papers of William Froude", The Institution of Naval Architects, London, 1955, pp.120-128.

Gao, P, Abrahams, A. D. (2004). Bedload transport resistance in rough open-channel flows. Earth Surface Processes and Landforms, 29, pp.423–435.

Garcia, M. and Parker, G. (1993). Experiments on the entrainment of sediment into suspension by a dense bottom current, Journal of Geophysical Research-Oceans, 98 (C3), pp.4793-4807.

Gaur, M. L. and Mathur, B. S. (2003). Modeling event-based temporal variability of flow resistance coefficient, Journal of Hydrologic Engineering, 8 (5), pp.266-277.

Gejadze, I. Y. and Copeland, G. J. M. (2006). Open boundary control problem for Navier-Stokes equations including a free surface: adjoint sensitivity analysis, Computer and Mathematics with Applications, 52 (8-9), pp.1243-1268.

Gerard-Varet, D. and Masmoudi, N. (2010). Relevance of the slip condition for fluid flows near an irregular boundary, Communications in Mathematical Physics, 295 (1), pp.99-137.

Gerbeau, J.-F. and Perthame, B. (2001). Derivation of a viscous Saint-Venant system for laminar shallow water; numerical validation, Discrete and Continuous Dynamical Systems-Series B, 1 (1), pp.89-102.

Ghavasieh, A.-R., Poulard, C. and Paquier, A. (2001). Effect of roughened strips on flood propagation: assessment on representative virtual cases and validation, Journal of Hydrology, 318 (1-4), pp.121-137.

Gimenez, R. and Govers, G. (2001). Interaction between bed roughness and flow hydraulics in eroding rills, Water Resources Research, 37 (3), pp.791-799.

Gimenez, R., Planchon, O., Silvera, N. and Govers, G. (2004). Longitudinal velocity patterns and bed morphology interaction in a rill, Earth Surface Processes and Landforms, 29 (1), pp.105-114.

Gioia, G. and Bombardelli, F. A. (2001). Scaling and similarity in rough channel flows, Physical Review Letters, 88, 014501, doi: 10.1103/PhysRevLett.88.014501~~.~~

Govers, G. (1992). Evaluation of transporting capacity formulae for overland flow. In: Overland Flow Hydraulics and Erosion Mechanics, Parsons A. J. and Abrahams, A. D. (eds), UCL Press, London, pp.243-273.

Grant, G. E. (1997). Critical flow constrains flow hydraulics in mobile-bed streams: a new hypothesis, Water Resources Research, 33 (2), pp.349-358.

Grant, G. E., Swanson, F. J. and Wolman, M. G. (1990). Pattern and origin of stepped-bed morphology in high-gradient streams, Wetern Cascades, Oregon, Geological Society of America Bulletin, 102 (3), pp.340-352.

Gresho, P. M. and Sani, R. L. (1998). Incompressible Flow and the Finite Element Method,~~.~~ ~~Wiley~~John Wiley & Sons, Inc., New York, NY, USA~~.~~

Guinot, V. and Cappelaere, B. (2009). Sensitivity analysis of 2D steady-state shallow water flow. Application to the surface flow model calibration, Advances in Water Resources, 32 (4), pp.540-560.

Gumiere, S. J., Raclot, D., Cheviron, B., Davy, G., Louchart, X., Fabre, J. C., Moussa, R., Le Bissonnais, Y. (2011). MHYDAS-Erosion : a distributed single-storm water erosion model for agricultural catchment, Hydrological Processes, 25 (11), pp.1717-1728.

Hairsine, P. B. and Rose, C. W. (1992a). Modeling water erosion due to overland flow using physical principles. 1. Sheet flow, Water Resources Research, 28 (1), pp.237-243.

Hairsine, P. B. and Rose, C. W. (1992b). Modeling water erosion due to overland flow using physical principles. 2. Rill flow, Water Resources Research, 28 (1), pp.245-250.

Hallema, D. and Moussa, R. (2013). A model for distributed GIUH-based flow routing on natural and anthropogenic hillslopes, Hydrological Processes, 28, pp.4877-4895, doi~~DOI~~: 10.1002/hyp.9984.

Härtel, C. (1996). Turbulent flows: direct numerical simulation and large-eddy simulation, In: Handbook of Computational Fluid Mechanics, R. Peyret Ed., Elsevier, New York, pp.283-338.

**Mis en forme :** Espace Avant : 0 pt, Après : 0 pt

Hauke, G. (2002). A stabilized finite element method for the Saint-Venant equations with application to irrigation, International Journal for Numerical Methods in Fluids, 38 (10), pp.963-984.

Hayami, S. (1951). On the propagation of flood waves, Disaster Prevention Research Institute Bulletin, 1, pp.1-16.

Henderson, F.M. (1966). Open Channel Hydraulics. MacMillan and Co., New York.

Hénine, H., Nédélec, Y. and Ribstein, P. (2014). Coupled modelling of the effect of overpressure on water discharge in a tile drainage system. Journal of Hydrology, 511, pp.39–48.

Hessel, R. (2006). Consequences of hyperconcentrated flow for process-based soil erosion modelling on the Chinese Loess Plateau, Earth Surface Processes and Landforms, 31, pp.1100-1114.

Hessel, R., Jetten, V. and Ganghui, Z. (2003). Estimating Manning's n for steep slopes, Catena, 54, pp.77-91.

Hino, M. (1963) Turbulent flows with suspended particles, Journal of the Hydraulic Division ASCE, 89(2a), pp.161-185.

Hjulström, F. (1935), Studies of the morphological activity of rivers as illustrated by the river Fyris, Bulletin of the Geology Institute of Uppsala, 25, pp.221-527.

Hornberger, G.M. and Boyer, E. W. (1995). Recent advances in watershed modelling. US National report to the IUGG 1991–1994. Reviews of Geophysics, 33, Supplement S2, pp.949–957.

Horritt, M. S. and Bates, P. D. (2002). Evaluation of 1D and 2D numerical models for predicting river flood inundation, Journal of Hydrology, 268 (1-4), pp.87-99.

Horton, R. E. (1945). Erosional development of streams and their drainage basins: hydrological approach to quantitative morphology, Bulletin of the Geological Society of America, 56 (3), pp.275-370.

Howard, A. D. (1994). A detachment-limited model of drainage basin evolution, Water Resources Research, 30, pp.2261-2285.

Ikeda, S. (1982). Incipient motion of sand particles on side slopes, Journal of Hydraulic Engineering, 108, pp.95–114.

Iwagaki Y. (1955). Fundamental studies on the runoff analysis by characteristics, Disaster Prevention Research Institute Bulletin, 10, Kyoto, 25 pp.

Izumi, N. and Parker, G. (1995). Linear stability of channel inception: downstream-driven theory, Journal of Fluid Mechanics, 283, pp.341-363.

Jäger, W. and Mikelic, A. (2001). On the roughness-induced effective boundary conditions for an incompressible viscous flow, Journal of Differential Equations, 170 (1), pp.96-122.

Jäger, W. and Mikelic, A. (2003). Couette flow over a rough boundary and drag reduction, Communications in Mathematical Physics, 232, pp.429-455.

Jain, M. K. and Singh, V. P. (2005). DEM-based modelling of surface runoff using diffusive wave equation, Journal of Hydrology, 302, pp.107-126.

Jansons, K. M. (1988). Determination of the macroscopic (partial) slip boundary condition for a viscous flow over a randomly rough surface with a perfect slip microscopic boundary condition, Physics of Fluids, 31 (1), pp.15-17.

Järvelä, J. (2005). Effect of flexible vegetation on flow structure and resistance, Journal of Hydrology, 307, pp.233-241.

Jetten, V., de Roo, A. and Favis-Mortlock, D. (1999). Evaluation of field-scale and catchment-scale soil erosion models, Catena, 37 (3-4), pp.521-541.

Jetten, V., Govers, G. and Hessel, R. (2003). Erosion models: quality of spatial predictions, Hydrological Processes, 17, pp.887-900.

Johnson, R.W. (1998). Handbook of fluid dynamics~~mechanics~~, CRC Press, Boca Raton, FL, USA, 1952 pp.

Julien, P.Y. (2010). Erosion and sedimentation. Cambridge, UK~~ University Press~~.

Julien, P. Y. and Bounvilay, B. (2013). Velocity of rolling bed load particles, ASCE - Journal of Hydraulic Engineering, 139 (2), pp.177-186.

Julien, P. Y. and Simons, D. B. (1985). Sediment transport capacity of overland flow, Transactions of the American Society of Agricultural Engineers, 28 (3), pp.755-762.

Katopodes, N.D. (1982). On zero-inertia and kinematic waves, Journal of Hydraulic Engineering, American Society of Civil Engineers, 108(HY11), pp.1380-1385.

Katopodes, N. D. and Bradford, S. F. (1999). Mechanics of overland flow, Proceedings of the International Workshop on Numerical Modelling of Hydrodynamic Systems, Zaragoza, Spain, 21-24 June 1999.

Keshavarzy, A. and Ball, J. E. (1997). Analysis of the characteristics of rough bed turbulent shear stresses in an open channel, Stochastic Hydrology and Hydraulics, 11 (3), pp.193-210.

Keskin, M. E. and Agiralioglu, N. (1997). A simplified dynamic model for flood routing in rectangular channels, Journal of Hydrology, 202, pp.302–314.

Keulegan, G. H. (1938). Laws of turbulent flow in open channels, paper RP1151, Journal of Research, USA National Bureau of Standards, 21, pp.707-741.

Kim, J., Moin, P. and Moser, R. (1987). Turbulence statistics in fully-developed channel flow at low Reynolds number, Journal of Fluid Mechanics, 177, pp.133-166.

King, H. W. and Brater, E. F. (1963). Handbook of Hydraulics, 5th Ed., McGraw-Hill Book Company, New York.

Kirkby M.J. (1978). Hillslope Hydrology, John Wiley & Sons, Chichester, UK,~~.~~ 389 pp.

Kirkby, M. J. (1980). The stream head as a significant geomorphic threshold, in: D.R. Coates and J.D. Vitek (eds) Threshold in Geomorphology, London: George Allen and Unwin, pp.53-73.~~,~~

Klemes, V. (1986). Dilletantism in hydrology: Transition or destiny?, Water Resources Research, 22, pp.177-188.

Kline, S. J., Reynolds, W. C., Schraub, F. A. and Runstadler, P. W. (1967). The structure of turbulent boundary layers, Journal of Fluid Mechanics, 30 (4), pp.741-773.

Kneller, B. and Buckee, C. (2001). The structure and fluid mechanics of turbidity currents: a review of some recent studies and their geological implications, Sedimentology, 47 (Suppl.1), pp.62-94.

Knisel, W.G. (1980). Creams, a field scale model for chemicals, runoff and erosion from agricultural management systems. U. C. R. Report USDA no26.

**Mis en forme :** Espace Avant : 0 pt, Après : 0 pt

Koomey, J., Berard, S., Sanchez, M. and Wong, H. (2010). Implications of historical trends in the electrical efficiency of computing, IEEE Annals of the history of computing, 33 (3), pp.46-54.

Koussis, A. D. (1978). Theoretical estimation of flood routing parameters, Journal of the Hydraulic Division - ASCE, 104, HY1, pp.109-115.

Kramer, C. and Papanicolaou, A. (2005) The Effects of Relative Submergence on Cluster Formation in Gravel Bed Streams. Impacts of Global Climate Change: pp. 1-12.

Kuchment, L.S. (1972). Matematicheskoye modelirovanye rechnogo stoka (Mathematical Models of River Flow). Gidrometeoizdat, Leningrad, 190 pp. (in Russian).

Laflen, J. M., Lane, L. J. and Foster, G. R. (1991). A new generation in erosion-prediction technology, Journal of Soil and Water Conservation, 46, pp.34-38.

Lagrée, P.-Y. (2003). A triple-deck model of ripple formation and evolution, Physics of Fluids, 15 (8), pp.2355-2368.

Lajeunesse, E., Malverti, L., Lancien, P., Armstrong, L., Métivier, F., Coleman, S., Smith, C. E., Davies, T., Cantelli, A. and Parker, G. (2010). Fluvial and submarine morphodynamics of laminar and near-laminar flows, Sedimentology, 57, pp.1-26.

Lamarre, H. and Roy, A. (2008). The role of morphology on the displacement of particles in a step-pool river system, Geomorphology, 99, pp.270-279.

Lamb, M. P., Dietrich, W. E. and Venditti, J. G. (2008a). Is the critical Shields stress for incipient sediment dependent on channel-bed slope?, Journal of Geophysical Research-Earth Surface, 113, F02008.

Lamb, M. P., Dietrich, W. E. and Sklar, L. S. (2008b). A model for fluvial bedrock incision by impacting suspended and bed load sediment, Journal of Geophysical Research, 113, F03025.

Lane, S. N., Richards, K. S. and Chandler, J. H. (1994). Application of distributed sensitivity analysis to a model of turbulent open-channel flow in a natural river channel, Proceedings of the Royal Society of London Series A- Mathematical Physical and Engineering Sciences, 447 (1929), pp.49-63.

Langhaar, H. L. (1951). Dimensional Analysis and the Theory of Models, New York: Wiley, 166 pp.

Lawless, M. and Robert, A. (2001). Scales of boundary resistance in coarse-grained channels, turbulent velocity profiles and implications, Geomorphology, 39 (3-4), pp.221-238.

Lawrence, D. S. L. (1997). Macroscale surface roughness and frictional resistance in overland flow, Earth Surface Processes and Landforms, 22 (4), pp.365-382.

Lawrence, D. S. L. (2000). Hydraulic resistance in overland flow during partial and marginal surface inundation: experimental observations and modeling, Water Resources Research, 36 (8), pp.2381-2393.

Leonard, A. (1974). Energy cascade in large-eddy simulation of turbulent channel flow, Advances in Geophysics, 18, pp.237-248.

Leopold, L. B., Bagnold, R. A., Wolman, M. G. and Brush, L. M. Jr, (1960). Flow resistance in sinuous or irregular channels, U.S. Geological Survey Professional Paper 282-C, 134 pp.

Liggett, J. A. and Woolhiser, D. A. (1967). Difference solutions of the shallow-water equation, Journal of the Engineering Mechanics Division, ASCE-American Society of Civil Engineers, 93, pp.39-71.

Lighthill, M. J. and Whitham, G. B. (1955). On kinematic waves, 1. Flood movement in long rivers, Proceedings of the Royal Society – Series A, 229, pp.281-316.

Lilburne, L. (2002). The scale matcher: A framework for assessing scale compatibility of environmental data and models, PhD Thesis, University of Otago, Dunedin, New Zealand, 392 pp.

Lobkovsky, A. E., Orpe, A. V., Molloy, R., Kudrolli, A. and Rothman, D. H. (2008). Erosion of a granular bed driven by laminar fluid flow, Journal of Fluid Mechanics, 605, pp.47-58.

Loucks, D. P. and van Beek, E. (2005). Water Resources Systems Planning and Management - An Introduction to Methods, Models and Applications, Studies and Reports in Hydrology series, UNESCO Publishing / WL - Delft Hydraulics, 680 pp.

Lyn, D. A. (1992). Turbulence characteristics of sediment-laden flows in open channels, Journal of Hydraulic Engineering, 118 (7), pp.971-988.

Manes, C., Pokrajac, D., Coceal, O. and McEwan, I. (2008). On the significance of form-induced stress in rough wall turbulent boundary layers, Acta Geophysica, 56 (3), pp.845-861.

**Mis en forme :** Espace Avant : 0 pt, Après : 0 pt

**Mis en forme :** Anglais (États-Unis)

Mangeney, A., Bouchut, F., Thomas, N., Vilotte, J. P. and Bristeau, M. O. (2007). Numerical modelling of self-channeling granular flows and of their levee-channel deposits, Journal of Geophysical Research, 112, F02017.

Manning, R. (1871). On the flow of water in open channels and pipes, Transactions of the Institution of Civil Engineers of Ireland, 20, pp.161-207.

Marche, F. (2007). Derivation of a new two-dimensional viscous shallow water model with varying topography, bottom friction and capillary effects, European Journal of Mechanics B/Fluids, 26 (1), pp.49-63.

Mavriplis, D. (1998). On Convergence Acceleration Techniques for Unstructured Meshes. Technical Report ICASE No. 98-44 and NASA/CR-1998-208732, Institute for Computer Applications in Science and Engineering, NASA Langley Research Center.

Meile, T. (2007). Influence of macro-roughness of walls on steady and unsteady flow in a channel, PhD Thesis, Ecole Polytechnique Fédérale de Lausanne, 414 pp.

Mendoza, C. and Zhou, D. (1997). Energetics of sediment-laden streamflows, Water Resources Research, 33(1), pp.227-234.

Merritt, W.S., Letche, R.A. and Jakeman, A.J. (2003). A review of erosion and sediment transport models, Environmental Modelling and Software, 18, 761-799.

Métivier, F. and Meunier, P. (2003). Input and output flux correlations in an experimental braided stream: implications on the dynamics of the bed load transport, Journal of Hydrology, 271, pp.22-38.

Meyer-Peter, E. and Müller, R. (1948). Formulas for bed-load transport, Proceedings of the Second Meeting of IAHR, Stochkolm, pp.39-64.

Milliman, J.D. and Syvitski, J.P.M. (1992). Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers, Journal of Geology, pp.525-544.

Moore, G. E. (1965). Cramming More Components onto Integrated Circuits, Electronics, pp. 114–117.

Montgomery, D. R. and Buffington, J. M. (1997). Channel-reach morphology in mountain drainage basins, Geological Society of America Bulletin, 109 (5), pp.596-611.

**Mis en forme :** Anglais (Royaume-Uni)

**Mis en forme :** Anglais (États-Unis)

**Mis en forme :** Anglais (États-Unis)

**Mis en forme :** Anglais (États-Unis)

**Mis en forme :** Anglais (États-Unis)

Morgan, R. P. C., Quinton, J. N., Smith, R. E., Govers, G., Poesen, J., Auerwald, K., Chisci, G., Torri, D. and Styczen, M. E. (1998). The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments, Earth Surface Processes and Landforms, 23, pp.527-544.

Moussa, R. (1996). Analytical Hayami solution for the diffusive wave flood routing problem with lateral inflow, Hydrological Processes, 10 (9), pp.1209-1227.

Moussa, R. and Bocquillon, C. (1996a). Criteria for the choice of flood-routing methods in natural channels, Journal of Hydrology, 186 (1-4), pp.1-30.

Moussa, R. and Bocquillon, C. (1996b). Algorithms for solving the diffusive wave flood routing equation, Hydrological Processes, 10 (1), pp.105-124.

Moussa, R. and Bocquillon, C. (2000). Approximation zones of the Saint-Venant equations for flood routing with overbank flow, Hydrology and Earth System Sciences, 4(2), pp.251-261.

Moussa, R. and Bocquillon, C. (2009). On the use of the diffusive wave for modelling extreme flood events with overbank flow in the floodplain, Journal of Hydrology, 374, pp.116-135.

Moussa, R., Voltz, M. and Andrieux, P. (2002). Effects of the spatial organization of agricultural management on the hydrological behaviour of a farmed catchment during flood events, Hydrological Processes, 16, pp.393-412.

Moussa, R., Chahinian, N. and Bocquillon, C. (2007). Distributed hydrological modelling of a Mediterranean mountainous catchment - model construction and multi-site validation, Journal of Hydrology, 337, pp.35-51.

Mügler, C., Planchon, O., Patin, J., Weill, S., Silvera, N., Richard, P. and Mouche, E. (2010). Comparison of roughness models to simulate overland flow and tracer transport experiments under simulated rainfall at plot scale, Journal of Hydrology, 402, pp.25-40.

Mulder, T. and Alexander, J. (2001). The physical character of subaqueous sedimentary density flows and their deposits, Sedimentology, 48, pp.269-299.

Munier, S., Litrico, X., Belaud, G. and Malaterre, P.-O. (2008). Distributed approximation of open-channel flow routing accounting for backwater effects, Advances in Water Resources, 31, pp.1590-1602.

Muñoz-Carpena, R., Parsons, J. E. and Gillian, J. W. (1999). Modelling hydrology and sediment transport in vegetative filter strips, Journal of Hydrology, 214, pp.111-129.

Myers, T. G. (2003). Unsteady laminar flow over a rough surface, Journal of Engineering Mathematics, 46 (2), pp.111-126.

Nakagawa, H. and Nezu, I. (1977). Prediction of the contributions to the Reynolds stress from bursting events in open channel flows, Journal of Fluid Mechanics, 80, pp.99–128.

Nash, J. E. and Sutcliffe, J. V. (1970). River flow forecasting through conceptual models, part I - A discussion of principles, Journal of Hydrology, 10 (3), pp.282-290.

Navier, C. L. M. H. (1822). Mémoire sur les lois du mouvement des fluides, Mémoires de l'Académie Royale des Sciences de l'Institut de France, 6, pp.389-440.

Navier, C. L. M. H. (1827). Sur les lois de l'équilibre et du mouvement des corps élastiques, Mémoires de l'Académie Royale des Sciences de l'Institut de France, 7, pp.375-393.

Neill, C. R (1968). A re-examination of the beginning of movement for coarse granular bed materials. Report No. 68, Hydraulic Research Station, Wallingford, England.

Nelson, J.M., R.L. Shreve, D.C. McLean, and T.G. Drake (1995). Role of near-bed turbulence structure in bed load transport and bed form mechanics, Water Resources Research, 31(8), pp.2071-2086.

Nepf, H. (1999). Drag, turbulence, and diffusion in flow through emergent vegetation, Water Resources Research, 35 (2), pp.479-489.

Newton, I. (1687). Philosophiæ Naturalis – Principia Mathematica, 1st ed., London, UK, 512 pp.

Nezu, I. and Nekagawa, H. (1993). Turbulence in open-channel flows, Balkema, Rotterdam, The Netherlands, 286 pp.

Nikora, V., and D. Goring (2000), Flow turbulence over fixed and weakly mobile gravel beds, Journal of Hydraulic Engineering, 126 (9), pp.679-690.

Nikora, V., Goring, D., McEwan, I. and Griffiths, G. (2001). Spatially-averaged open-channel flow over a rough bed, Journal of Hydraulic Engineering-ASCE, 127 (2), pp.123-133.

Nikora, V., Larned, S., Nikora, N., Debnath, K., Cooper, G. and Reid, M. (2008). Hydraulic resistance due to aquatic vegetation in small streams: field study, Journal of Hydraulic Engineering, 134 (9), pp.1326-1332.

Nino, Y., Lopez, F. and Garcia, M. (2003). Threshold for particle entrainment into suspension, Sedimentology, 50 (2), pp.247-263.

Nord, G. and Esteves, M. (2010). The effect of soil type, meteorological forcing and slope gradient on the simulation of internal erosion processes at the local scale, Hydrological Processes, 24 (13), pp.1766-1780.

Ouriémi, M., Aussillous, P., Medale, M., Peysson, Y. and Guazzelli, E. (2007). Determination of the critical Shields number for particle erosion in laminar flow, Physics of Fluids, 19, 061706.

Paiva, R. C. D., Collischonn, W. and Buarque, D. C. (2013). Validation of a full hydrodynamic model for large-scale hydrologic modelling in the Amazon, Hydrological Processes, 27, pp.333-346.

Panton, R. L. (1984). Incompressible Flow, John Wiley and Sons, New York, 780 pp.

Paola, C., Heller, P. L. and Angevine, C. L. (1992). The large-scale dynamics of grain-size variation in alluvial basins. I: Theory, Basin Research, 4, pp.73-90.

Paola, C., Straub, K., Mohrig, D. and Reinhardt, L. (2009). The "unreasonable effectiveness" of stratigraphic and geomorphic experiments, Earth-Science Reviews, 97, pp.1-43.

Papanicolaou, A. N., Diplas, P., Dancey, C. L. and Balakrishnan, M. (2001). Surface roughness effects in near-bed turbulence: implications to sediment entrainment, Journal of Engineering Mechanics, 127, pp.211-218.

Parker, G. (1976). On the cause and characteristic scales of meandering and braiding in rivers, Journal of Fluid Mechanics, 76, pp.457-480.

Parker, G. (1978a). Self-formed straight rivers with equilibrium banks and mobile bed. Part 1: the sand-silt river, Journal of Fluid Mechanics, 89 (1), pp.109-125.

Parker, G. (1978b). Self-formed straight rivers with equilibrium banks and mobile bed. Part 2: the gravel river, Journal of Fluid Mechanics, 89 (1), pp.127-146.

Parker, G. and Coleman, N. L. (1986). Simple model of sediment-laden flows, Journal of Hydraulic Engineering, 112(2b), pp.356-375.

Parker, G., Fukushima, Y. and Pantin, H. M. (1986). Self-accelerating turbidity currents, Journal of Fluid Mechanics, 171, pp.145-181.

Parsons, A. J. and Abrahams, A. D. (1992). Overland flow: hydraulics and erosion mechanics, Chapman & Hall, New-York, 438 pp.

Parsons, A. J., Wainwright, J., Abraham, A. D. and Simanton, J. R. (1997). Distributed dynamic modelling of interrill overland flow. Hydrological Processes, 11, pp.1833-1859.

Parsons, A. J., Brazier, R. E., Wainwright, J. and Powell, M. E. (2003). Scale relationships in hillslope runoff and erosion, Earth Surface Processes and Landforms, 31 (11), pp.1384-1393.

Perkins, S. P. and Koussis, A. D. (1996). Stream-aquifer interaction model with diffusive wave routing, Journal of Hydraulic Engineering, 122 (4), pp.210-218.

Perumal, M. and Price, R. K. (2013). A fully mass conservative variable parameter McCarthy–Muskingum method: Theory and verification, Journal of Hydrology, 502, pp.89–102.

Peyras, L., Royet, P. and Degoutte, G. (1992). Flow and energy dissipation over stepped gabion weirs, Journal of Hydraulic Engineering – ASCE, 118 (5), pp.707-717.

Pickup, G. and Marks, A. (2001). Regional scale sedimentation process models from airborne gamma ray remote sensing and digital elevation data, Earth Surface Processes and Landforms, 26, pp.273-293.

Pokrajac, D., Campbell, L. J., Nikora, V., Manes, C. and McEwan, I. (2007). Quadrant analysis of persistent spatial velocity perturbations over square-bar roughness, Experiments in Fluids, 42 (3), pp.413-423.

Polyakov, V. O. and Nearing, M. A. (2003). Sediment transport in rill flow under deposition and detachment conditions, Catena, 51 (1), pp.33-43.

Ponce, V. M. (1990). Generalized diffusive wave equation with inertial effects, Water Resources Research, 26 (5), pp.1099-1101.

Ponce, V. M. and Simons, D. B. (1977). Shallow wave propagation in open channel flow, Journal of the Hydraulic Division, American Society of Civil Engineers, 103(HY12), pp.1461-1476.

Ponce, V. M., Li, R. M. and Simons, D. B. (1978). Applicability of kinematic and diffusion models, Journal of the Hydraulic Division, American Society of Civil Engineers, 104 (HY3), pp.353-360.

Ponce, V. M., Lohani, A. K. and Scheyhing, C. (1996). Analytical verification of Muskingum-Cunge routing, Journal of Hydrology, 174, pp.235-241.

Powell, D. M. (2014). Flow resistance in gravel-bed rivers: progress in research, Earth Science Reviews, 136, pp.301-338.

Prahl, L., Holzer, A., Arlov, D., Revstedt, J., Sommerfeld, M. and Fuchs, L. (2007), On the interaction between two fixed spherical particles, International Journal of Multiphase Flow, 33 (7), pp.707-725.

Priezjev, N. and Troian, S. (2006). Influence of periodic wall roughness on the slip behaviour at liquid/solid interfaces: molecular-scale simulations versus continuum predictions, Journal of Fluid Mechanics, 554, pp.25-46.

Prosser, I. P. and Rustomji, P. (2000). Sediment transport capacity for overland flow, Progress in Physical Geography, 24 (2), pp.179-193.

Prosser, I. P., Dietrich, W. E. and Stevenson, J. (1995). Flow resistance and sediment transport by concentrated overland flow in a grassland valley, Geomorphology, 13, pp.71-86.

Rathburn, S. and Wohl, E. (2003). Predicting sediment dynamics along a pool-riffle mountain channel, Geomorphology, 55, pp.111-124.

Raupach, M. R. (1981). Conditional statistics of Reynolds stress in rough-wall and smooth-wall turbulent boundary layers, Journal of Fluid Mechanics, 108, pp.363-382.

Rauws, G. (1980). Laboratory experiments on resistance to overland flow due to composite roughness, Journal of Hydrology, 103, 37–52.

Rayleigh (1877). Theory of sound, Macmillan, London, UK.

Reddy, K. V., Eldho, T. I., Rao, E. P. and Hengade, N. (2007). A kinematic-wave-based distributed watershed model using FEM, GIS and remotely sensed data, Hydrological Processes, 21 (20), pp.2765–2777.

Reynolds, O. (1883). An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels. Philosophical Transactions of the Royal Society of London (A), 174, pp.935–982.

Reynolds, O. (1895). On the dynamical theory of incompressible viscous fluids and the determination of the criterion, Philosophical Transactions of the Royal Society of London (A), 186, pp.123-164.

Riabouchinsky, D. (1911). Méthode des variables de dimension zero et son application en aérodynamique, L'aérophile, 19, pp.407-408.

Richardson, S. (1973). On the no-slip boundary condition, Journal of Fluid Mechanics, 59 (4), pp.707-719.

Ritchie, J.C. and McHenry, J.R (1990). Application of Radioactive Fallout Cesium-137 for Measuring soil erosion and sediment accumulation rates and patterns: A review. Journal of Environmental Quality, 19, pp.215-233.

Roche, N. (2006). Modélisation du ruissellement sur surfaces rugueuses, PhD Thesis, Université Joseph Fourier, Grenoble, France, 213 pp.

Rodellar, J., Gomez, M. and Bonet, L. (1993). Control method for on-demand operation of open-channel flow, Journal of Irrigation and Drainage Engineering, 119, pp.225-241.

Rödi, W. (1988). Turbulence models and their application in hydraulics - a state of the art review, International Association for Hydraulic Research, Delft, The Netherlands, 47p.

Romanowicz, R.J., Dooge, J.C.I., and Kundzewicz, Z.W. (1988). Moments and cumulants of linearized St. Venant equation, Advances in Water Resources, 11, 92-100.

Rosgen, D. L. (1994). A classification of natural rivers, Catena, 22 (3), pp.169-199.

Roux, H. and Dartus, D. (2006). Use of parameter optimization to estimate a flood wave: Potential applications to remote sensing of rivers, Journal of Hydrology, 328, pp.258– 266.

**Mis en forme :** Espace Avant : 0 pt, Après : 0 pt

**Mis en forme :** Anglais

Rutschmann, P. and Hager, W. H, (1996). Diffusion of floodwaves, Journal of Hydrology, 178, pp.19-32.

Saint-Venant, A. J.-C. B. de (1871). Théorie du mouvement non permanent des eaux, avec application aux crues des rivières et à l'introduction des marées dans leur lit, Comptes-Rendus de l'Académie des Sciences, 73, pp.147-154 and 237-240.

Saleh, F, Ducharme, A., Flipo, N., Oudin, L. and Ledoux, E. (2013). Impact of river bed morphology on discharge and water levels simulated by a 1D Saint–Venant hydraulic model at regional scale, Journal of Hydrology, 476, pp.169–177.

Sander, G. C., Parlange, J. Y., Barry, D. A., Parlange, M.B. and Hogarth, W. L. (2007). Limitation of the transport capacity approach in sediment transport modeling, Water Resources Research, 43 (2), W02403, doi: 10.1029/2006WR005177~~.~~

Sau, J., Malaterre, P.-O. and Baume, J.-P. (2010). Sequential Monte-Carlo state estimation of an irrigation canal, Comptes-Rendus Mecanique, 338, pp.212-219.

Savage, S. B. and Hutter, K. (1989). The motion of a finite mass of granular material down a rough incline, Journal of Fluid Mechanics, 199, pp.177-215.

Savage, S. B. and Hutter, K. (1991). The dynamics of avalanches of granular materials from initiation to runout. Part I: Analysis, Acta Mechanica, 86, pp.201-223.

Schlichting H. (1936). Experimentelle Untersuchungenzum Rauhigkeitsproblem Ing.Arch. 7:1–34. (Engl. transl. 1937. Experimental investigation of the problem of surface roughness. NACA TM 823)

Schmeeckle, M. W. and Nelson, J. M. (2003). Direct numerical simulation of bedload transport using a local, dynamic boundary condition, Sedimentology, 50 (2), pp.279-301.

Schmeeckle, M. W., Nelson, J. M. and Shreve, R. L. (2007). Forces on stationary particles in near-bed turbulent flows, Journal of Geophysical Research-Earth Surface, 112 (F2), F02003, doi: 10.1029/2006JF00536.

Sear, D. A. (1996). Sediment transport processes in pool-riffle sequences, Earth Surface Processes and Landforms, 21, pp.241-262.

Sen, D. J. and Garg, N. K. (2002). Efficient algorithm for generally varied flows in channel networks, Journal of Irrigation and Drainage Engineering, 128 (6), pp.351-357.

Sharifi, S., Sterling, M. and Knight, D. W. (2009). A novel application of a multi-objective evolutionary algorithm in open channel flow modelling, Journal of Hydroinformatics, 11(1), pp.31-50.

Sheets, B., Hickson, T.A., and Paola, C. (2002). Assembling the stratigraphic record: Depositional patterns and time-scales in an experimental alluvial basin, Basin Research, 14, pp.287–301.

Shields, A. (1936). Anwendung der Änlichtkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung, Mitteilungen der Preuβischen Versuchsanstalt für Wasserbau und Schiffbau No.6, Berlin, Germany. (English translation by W. P. Ott and J. C. van Uchelen, Hydrodynamics Laboratory Publication No.167, Hydrodynamics Laboratory of the California Institute of Technology, Pasadena, USA).

Simpson, G. and Castelltort, S. (2006). Coupled model of surface water flow, sediment transport and morphological evolution, Computers & Geosciences, 32 (10), pp.1600-1614.

Sivakumaran, N. S. and Yevjevich, V. (1987). Experimental verification of the Dressler curved-flow equations, Journal of Hydraulic Research, 25 (3), pp.373-391.

Sivapalan, M., Bates, B. C. and Larsen, J. E. (1997). A generalized, non-linear, diffusion wave equation: theoretical development and application, Journal of Hydrology, 192, pp.1-16.

Sklar, L. S. and Dietrich, W. E. (2004). A mechanistic model for river incision into bedrock by saltating bed load, Water Resources Research, 40, W06301, doi: 10.1029/2003WR002496.~~.~~

Slaymaker, O. (2006). Towards the identification of scaling relations in drainage basin sediment budgets, Geomorphology, 80, pp.8–19.

Smagorinsky, J. (1963). General circulation experiments with the primitive equations, Monthly Weather Review, 91 (3), pp.99-164.

Smart, G. M. (1984). Sediment transport formula for steep channels, Journal of Hydraulic Engineering, 110 (3), pp.267-276.

Smith, J. D. and McLean S. R. (1977). Spatially averaged flow over a wavy surface, Journal of Geophysical Research, 82, pp.1735-1746.

Smith, M. W., Cox, N. J. and Bracken, L. J. (2007). Applying flow resistance equations to overland flows, Progress in Physical Geography, 31, pp.363-387.

**Mis en forme :** Espace Avant : 0 pt, Après : 0 pt

**Mis en forme :** Anglais (Royaume-Uni)

Smith, R. E., Goodrich, D. C., Woolhiser, D. A. and Unkrich, C. L. (1995). KINEROS – a kinematic runoff and erosion model. In: Computer Models of Watershed Hydrology, Singh, V. P. (ed.), Water Resources: Littleton, CO, pp.697-732.

Stein, O.R., Alonso, C.V. and Julien, P.Y. (1993). Mechanics of jet scour downstream of a headcut, Journal of Hydraulic Research, 31 (6), pp.723-738.

Stevenson, P., Thorpe, R. B. and Davidson, J. F. (2002). Incipient motion of a small particle in the viscous boundary layer at a pipe wall, Chemical Engineering Science, 57 (21), pp.4505-4520.

Stoker, J. J. (1957~~8~~). Water waves, the mathematical theory with application, Wiley, Interscience Publishers, New York, USA, 357~~600~~ pp.

Stokes, G. G. (1845). On the theories of internal friction of fluids in motion, Transactions of the Cambridge Philosophical Society, 8, pp.287-319.

Strahler, A.N. (1956). The nature of induced erosion and aggradation. In: Thomas, W.L. (Ed.), Man's Role in Changing the Face of the Earth. University of Chicago Press, Chicago, pp.621–638.

Sundaresan, S., Eaton, J., Koch, D. L. and Ottino, J. M. (2003). Appendix 2: Report of study group on disperse flow, International Journal of Multiphase Flow, 29, pp.1069-1087.

Sutherland, A.J. (1967), Proposed mechanism for sediment entrainment by turbulent flows,Journal of Geophysical Research, 72, pp.6183-6194.

Syvitski, J.P.M. and Milliman, J.D. (2007). Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean, Journal of Geology, 115 (1), pp.1-19.

Tatard, L., Planchon, O., Wainwright, J., Nord, G., Favis-Mortlock, D., Silvera, N., Ribolzi, O., Esteves, M., Huang, C. H. (2008). Measurement and modeling of high-resolution flow-velocity data under simulated rainfall on a low-slope sandy soil, Journal of Hydrology, 348 (1-2), pp1-12.

Tiemeyer, B., Moussa, R., Lennartz, B. and Voltz, M. (2007). MHYDAS-DRAIN : a spatially distributed model for small, artificially drained lowland catchments, Ecological Modelling, 209 (1), pp.2-20.

Todini, E. and Bossi, A. (1986). PAB (Parabolic and Backwater) : an unconditionnally stable flood routing scheme particularly suited for real time forecasting and control, Journal of Hydraulic Research, 24 (5), pp.405-424.

Trigg, M. A., Wilson, M. D., Bates, P. D., Horritt, M. S., Alsdorf, D. E., Forsberg, B. R. and Vega, M. C. (2009). Amazon flood wave hydraulics, Journal of Hydrology, 374 (1-2), pp.92-105.

Turek, S. (1999). Efficient Solvers for Incompressible Flow Problems,~~.~~ Springer, Berlin, Germany, 352 pp.

Van Heijst, M. W. I. M., Postma, G., Meijer, X. D., Snow, J. N. and Anderson, J. B. (2001). Quantitative analogue flume-model study of River-shelf systems: principles and verification examplified by the late quaternary Colorado River-delta evolution, Basin Research, 13, pp.243-268.

Van Maren, D. S. (2007). Grain size and sediment concentration effects on channel patterns of silt-laden rivers, Sedimentary Geology, 202, pp.297-316.

Van Rijn, L. C. (1984a). Sediment transport, part I: bed load transport, Journal of Hydraulic Engineering, 110, pp.1431-1456.

Van Rijn, L. C. (1984b). Sediment transport, part II: suspended load transport, Journal of Hydraulic Engineering, 110, pp.1613-1641.

Vanoni, V.A. (1946). Transportation of suspended sediment by water, Transactions of the A.S.C.E, 111,pp.67-133.

Vaschy, A. (1892). Sur les lois de similitude en physique, Annales Télégraphiques, 19, pp.25-28.

Vieux, B. E., Cui, Z. and Gaur, A. (2004). Evaluation of a physics-based distributed hydrologic model for flood forecasting, Journal of Hydrology, 298, pp.155–177.

Wainwright, J., Parsons, A. J., Müller, E. N., Brazier, R. E., Powell, D. M. and Fenti, B. (2008). A transport-distance approach to scaling erosion rates: I. Background and model development, Earth Surface Processes and Landforms, 33 (5), pp.813-826.

Walling, D.E. (1983). The sediment delivery problem, Journal of Hydrology, 65, pp.209-237.

Wang, G. T and Chen, S. (2003). A semi-analytical solution of the Saint-Venant equations for channel flood routing, Water Resources Research, 39 (4), 1076, doi:10.1029/2002WR001690.

Wang, G. T., Yao, C., Okoren, C. and Chen, S. (2006). 4-Point FDF of Muskingum method based on the complete St Venant equations, Journal of Hydrology, 324, pp.339–349.

Wang, L, Wu, J. Q., Elliot, W. J., Fiedler, F. R. and Lapin, S. (2014). Linear diffusion wave channel routing using a discrete Hayami convolution method, Journal of Hydrology, 509, pp.282-294.

Wang, Y, Straub, K. M. and Hajek, E. A. (2011). Scale-dependent compensational stacking: an estimate of time scales in channelized sedimentary deposits, Geology, 39 (9), pp.811-814.

Weichert, R. (2006). Bed morphology and stability of steep open channels, PhD Thesis, Technische Hochschule, Zürich, 265 pp.

Weisbach, J. (1845). Lehrbuch der Ingenieur- und Maschinen-Mechanik, Vieweg und Sohn eds., Braunschweig.

Whitham, G. B. (1999). Linear and nonlinear waves. John Wiley & Sons Inc., New York.

Wiberg, P. L. and Smith, J. D. (1987). Calculations of the critical shear stress for motion of uniform and heterogeneous sediments. Water Resources Research, 23, pp.1471–1480.

Williams G. P. (1970). Flume width and water depth effects in sediment-transport experiments. US Geological Survey Professional Paper 562-H.

Wright, S. and Parker, G. (2004). Flow Resistance and Suspended Load in Sand-Bed Rivers: Simplified Stratification Model, Journal of Hydraulic Engineering, 130 (8), pp.796-805.

Wu, R. M. and Lee, D. J. (2001). Hydrodynamic drag on non-spherical floc and free-settling test, Water Research, 35 (13), pp.3226-3234.

Yager, E. M., Kirchner, J. W. and Dietrich, W. E. (2007). Calculating bed load transport in steep boulder bed channels, Water Resources Research, 43, W07418, doi: 10.1029/2006WR005432~~.~~

Yalin, M. S. (1977). Mechanics of sediment transport. Pergamon Press, Oxford, UK, 2nd ed, 298 pp.

Yang, C. T. (1974). Unit stream power and sediment transport, Journal of the Hydraulics Division-ASCE, 100 (NHY9), pp.1269-1272.

Zanke, U. C. E. (2003). On the influence of turbulence on the initiation of sediment motion, International Journal of Sediment Research, 18 (1), pp.17-31.

Zhou, J. G. (1995). Velocity-depth coupling in shallow-water flows, Journal of Hydraulic Engineering, 121 (10), pp.717-724.

Zimmermann, A. and Church, M. (2001). Channel morphology, gradient profiles and bed stresses during flood in a step-pool channel, Geomorphology, 40 (3-4), pp.311-327.

Zoppou, C. and O’Neill, I. C. (1982). Criteria for the choice of flood routing methods in natural channels, Hydrology and Water Resources, Symposium, 11-13 May 1982, Melbourne, pp.75-81.